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FULL-SCALE SUBSONIC WIND TUNNEL REQUIREMENTS AND DESIGN STUDIES

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SUMMARY

This paper summarizes the justification and requirements for a large subsonic wind tunnel capable of testing full-scale aircraft, rotor systems, and advanced V/STOL aircraft propulsion systems. The design considerations and constraints for such a facility are reviewed, and the trades between facility test capability and costs are discussed. The design studies showed that the structural cost of this facility is the most important cost factor. For this reason (and other considerations such as requirements for engine exhaust gas purging) an open-return wind tunnel having two test sections was selected. The major technical problem in the design of an open-return wind tunnel is maintaining good test section flow quality in the presence of external winds. This problem has been studied extensively, and inlet and exhaust systems which provide satisfactory attenuation of the effects of external winds on test section flow quality were developed.

INTRODUCTION

The studies reported here were initiated in 1967 when the Aeronautics and Astronautics Coordinating Board (AACB) requested a general study to determine the need for new national aeronautics facilities. The Aeronautics Panel of the AACB organized three working groups to consider facility requirements for three types of aircraft: (a) subsonic and V/STOL; (b) transonic and supersonic; and (c) hypersonic.

In 1968 the Subsonic and V/STOL Working Group identified the need for a large subsonic wind tunnel capable of testing full-scale rotor systems and high performance V/STOL aircraft. Over the next two years the Aeronautics Panel reviewed the justification and technology requirements for the facilities proposed by the Working Groups and, in October 1970, recommended to the AACB that a large engine test facility and the large subsonic wind tunnel described herein be constructed. In December 1970, NASA organized an Inter-Center Working Group (comprised of personnel from NASA Headquarters and the Ames, Langley, and Lewis Research Centers) to conduct further design studies of the Full-Scale Subsonic Wind Tunnel. In February 1972, this Group selected a two-test section, open-return wind tunnel concept for this facility. Further design optimization studies are presently in progress.

One of the prime factors which motivated the AACB to initiate the study to determine the need for new aeronautical facilities was the recognition that improvements in effectiveness and economy of aeronautical systems have only been achieved by the extensive use of ground-based facilities. Another important factor was the recognition by the AACB that the United States had not initiated any new major aeronautical facilities since the Unitary Wind Tunnel program in 1950.

In their original instructions to the Subsonic and V/STOL Working Group the Aeronautics Panel of the AACB directed the Working Group to consider planned future aircraft programs and the facilities required for the development of these aircraft. To support this effort the advanced planning groups of the various military services and NASA submitted requirements for various military and commercial missions. Several points became clear. First, it was obvious that the facility could not be built soon enough to contribute to the development of specifically planned aircraft; so the Working Group interpreted the more generalized long-range mission requirements in terms of aircraft for the more distant future. Second, this exercise showed that the basic aircraft development trends and technical problems which justify the facility are more fundamental and more certain than specific aircraft development programs. And, third, there was no single absolute requirement in terms of either aircraft or problem solution which would justify the facility, but there were numerous technical problems for which the proposed facility would provide solutions in such an effective and efficient manner that it could be expected to pay for itself many times over. This situation makes the presentation and substantiation of the justification a protracted process. In brief, however, the points which will be made are as follows:

1. There is a rapidly growing demand for improved and increased transportation caused by the growing economy and population of the nation. Meeting this demand will far overtax our present transportation systems, and is critical for improvement of the quality of life in this country. Traffic congestion and aircraft noise are a key retardants to the development of adequate transportation.

2. The use of STOL, VTOL, and other high lift technology aircraft will provide solutions for a significant part of the transportation requirement. These same technologies are required for a number of military missions.

3. The key problem in the development of these aircraft is the reduction of the technical and financial risk of the aircraft development program. This program risk can be reduced by testing the critical components of the aircraft (e.g. V/STOL propulsion systems and rotors) at an early stage in the development effort, so that expensive and possibly catastrophic failures are avoided later in flight.

FUTURE AIR TRANSPORTATION REQUIREMENTS

Civil Requirements

A number of studies have documented the growing problems in providing the transportation facilities required to contend with the estimated growth in population and economy of the United States. For example, the domestic airlines alone expect the number of passenger miles flown in 1980 to be more than double that flown in 1970 (see reference 1). An even greater increase is expected in air cargo operations. When viewed in the context of the current congestion at large airports, it is clear that a major technical challenge must be met if the forecasted transportation capability is to be realized.

Figure 1 shows the major problem areas for civil air transportation as identified by the Joint DOT-NASA Civil Aviation Research and Development Policy Study (reference 1) along with the associated technological disciplines. With the exception of avionics, all of these disciplines would benefit from the type of facility proposed in this report.

The economic impact of aircraft noise and congestion is well documented. For example, figure 2 (taken from reference 2) shows that congestion around our major airports cost the airlines nearly 160 million dollars in 1969. It is estimated in reference 2 that the accompanying cost to passengers due to terminal area delays was an additional 100 million dollars. It is further estimated in reference 2 that these losses will grow to 600 million dollars for the airlines and 400 million dollars for passengers by 1980 unless corrective action is taken. The economic and environmental impact of the aircraft noise problem has been the subject of a number of reports and will not be further discussed herein. Suffice it to say that the problems of aircraft noise and air traffic congestion are exacting significant economic and environmental penalties at the present time. Further, if these problems are not adequately dealt with they will seriously limit the transportation capability of the nation and the growth of the air transportation industry.

Application of high-lift and V/STOL aircraft technology to civil aviation requirements.- References 3 through 10 show that the use of reduced takeoff and landing (RTOL) aircraft and V/STOL aircraft can be expected to provide significant relief of the aircraft congestion and noise problems. As shown in figure 3, this will be accomplished by shifting most of the short-haul traffic away from the major airports to small V/STOL ports. This should have a major impact on congestion since over 50 percent of the air traffic is presently funneled into only 14 major airports. Moreover, the major transportation demand for all scheduled carriers (both air and surface) is for trips between 50 and 500 miles. In addition to relieving the air traffic congestion and noise problem the high-performance RTOL or V/STOL transport also will produce large savings in total time required for trips of this stage length. These savings accrue from two factors. First, the takeoff and landing facilities can be closer to the passenger's destination with resulting savings in the time and cost of ground transportation to and from the airport. Second, the improved low-speed flight capability of the aircraft makes it possible to reduce the time lost in air and ground maneuvers in the terminal area and thereby to reduce the required airport- to-airport time.

Figure 4 (taken from reference 11) shows the noise impact of various forms of transportation systems, both air and ground. This figure shows that the use of V/STOL aircraft significantly reduces the land area exposed to high noise levels compared to that for conventional aircraft (CTOL). Moreover, for trip lengths more than 50 miles the air systems expose less land to excessive noise than the ground transportation systems. This is due to the fact that the aircraft is far removed from any potential listener through the major portion of its trip. Also shown in figure 4 is the amount of land which must be acquired for the use of the transportation systems. The air systems have an obvious advantage here since no extensive rights-of-way are required, and the use of V/STOL aircraft maximizes this advantage, since it minimizes the amount of land which must be acquired for airports.

The basic economic and environmental factors just discussed are not new. As a matter of fact, these are essentially the same factors which have historically driven the development of high-lift systems on aircraft and which have produced the improvements in maximum lift coefficient shown on figure 5. Present short and medium range jet transport aircraft are equipped with very sophisticated mechanical high lift devices. Further reductions in take-off and landing distances and the associated benefits of improved low-speed flight capability can only be achieved through the use of the powered-lift technology of V/STOL aircraft. Thus, the present interest in V/STOL transport aircraft is a logical extension of the high-lift technology trends for conventional aircraft.

Other civil applications of V/STOL aircraft.- The preceding discussion has been directed at the application of V/STOL aircraft to scheduled commercial transport operations. It should be noted, however, that there are many other uses for V/STOL aircraft. For example, the heavy-lift helicopter has already shown its value in many missions, both commercial and military. The helicopter is being used as a utility transport in a variety of commercial applications in spite of its deficiencies. This in itself is a testimony to the economic value of the utility provided by vertical flight capability. For example, the use of helicopters for carrying personnel and equipment to and from the off-shore oil rigs along the Gulf coast alone has accounted for more than 1 million flight hours.

Summary of civil aircraft requirements.- It is clear that basic factors such as the growth of the population and economy of this country will create a rapidly growing demand for transportation; and it is equally clear that the quality of life in the United States will be determined in a large part by how well these transportation requirements are dealt with. While there is room for debate about the level of growth in the transportation requirement, there can be no doubt that transportation capabilities will be taxed to the utmost. This is already evident in terms of the air and ground congestion in and around metropolitan areas. The potential of aircraft utilizing V/STOL technology to provide solutions for a significant part of this transportation requirement has been documented in a number of studies. The solution of the technical problems associated with the development of such aircraft constitutes a large part of the requirement for the proposed full-scale wind tunnel, as will be shown in a subsequent discussion of V/STOL aircraft technology.

Military Requirements

Conventional aircraft.- Many of the aircraft mission requirements dictated by military operations impose stringent requirements on landing and takeoff performance, low-speed flight characteristics, stall and spin characteristics, etc. For example, the achievement of satisfactory landing and takeoff characteristics for carrier-based aircraft without penalizing high speed performance requires a careful compromise between high-lift aerodynamics, high-speed aerodynamics, structural weight, and complexity. A similar situation exists for most tactical aircraft since they are required to use small unprepared fields which place a premium on landing and takeoff characteristics. Even large, long range military transports have generally quite stringent takeoff and landing specifications compared to their commercial counterparts. For example, the C5-A military transport is required to operate out of 4000-ft. fields with a 100,000 lb. payload.

V/STOL aircraft.- The value of V/STOL aircraft in a limited war situation has been proven by the widespread use of the helicopter in Vietnam for such missions as transportation, air-rescue operations, reconnaissance, tactical support of ground forces, and recovery of downed aircraft and other equipment from hostile territory. In a less constrained military situation where the enemy may be able to attack large air bases with either conventional or nuclear weapons, dispersal of aircraft to a number of small sites will be mandatory for survival. The vulnerability of large air bases (and aircraft that need long runways) has been demonstrated on a number of occasions, one of the most recent being the destruction of the Egyptian Air Force on the ground by the Israeli Air Force at the outset of the 1967 conflict.

As mentioned previously, the AACB requested the military services to review their long-range requirements for aeronautical weapons systems to help determine the ground-based facilities required to develop these systems. The requirements included a heavy-lift helicopter, a variety of V/STOL transports, anti-submarine warfare aircraft, rescue aircraft, and V/STOL fighters and tactical aircraft. The aircraft performance requirements for many of these missions dictate V/STOL aircraft with considerably higher speed capability than is available from conventional helicopters.

BASIC TECHNOLOGY PROBLEMS

Conventional Aircraft

As previously discussed in connection with figure 5, the problems of air traffic congestion, noise, and airport economics have forced a long-term trend towards higher maximum lift coefficients. A fundamental problem encountered in the design of high lift systems is the prediction of the full-scale flight characteristics near maximum lift from data obtained from wind tunnel tests of small scale models. There are two aspects to this problem. First, the model tests are conducted at considerably lower Reynolds numbers than those for full-scale flight conditions. Second, there may exist subtle, but important, differences between the model and the full-scale aircraft. Typical of these differences are leakage through the structure, deformation of flaps and slats under load, exhausting cooling air in regions of marginal flow stability, surface discontinuities, roughness, brackets, etc., all of which are details of the full-scale structure which cannot be duplicated at model scale. When discrepancies occur between predicted and actual flight characteristics, it is usually impossible to tell whether the cause is due to the difference in Reynolds number or to detailed differences between the model and the actual aircraft. The full-scale wind tunnel is a valuable tool in developing satisfactory high-lift systems and in defining discrepancies between predicted and actual performance, so that design procedures can be improved.

Low-Disk Loading V/STOL Aircraft

The main technical problem areas for low-disk loading V/STOL aircraft are rotor control, dynamic stability, dynamic loads, and performance at high flight speeds. These characteristics are highly dependent on the unsteady aerodynamic force inputs to the rotor and the dynamic characteristics of the rotor and its control system (including such real-world factors as backlash, break-out forces, and nonlinear effects). The unsteady aerodynamic forces on the rotor system are critically dependent on Mach number, Reynolds number, and advance ratio. Therefore, wind tunnel tests must be conducted at flight values of these parameters if they are to be meaningful.

Figure 6 (from reference 12) provides a graphic illustration of the complexity of the aerodynamic phenomena encountered by a rotor blade. On the advancing blade (where the rotor rotational velocity and the aircraft flight velocity add) there are compressibility and shock wave effects. The local Mach number, angle of attack, skew angle, Reynolds number, and dynamic pressure vary both with time (i.e., blade azimuth) and with radial location. On the retreating blade high angles of attack and dynamic stall are encountered. In some flight regimes the blade may encounter the vortex system shed by the preceding blade with accompanying impulsive loadings which produce both vibration and noise. In each revolution the blade encounters most of the aerodynamic problems faced on a fixed wing aircraft, and these problems are compounded by the dynamic environment of the rotor.

The dynamics problem of rotary wing aircraft is graphically illustrated on figure 7 (also taken from reference 12). The rotor itself is a flexible system deriving much of its stiffness from centrifugal force effects. It has many elastic modes, with significant coupling effects through inertia, structural, and aerodynamic effects, and these are often subtle and easily overlooked or inadequately accounted for. The rotor itself is flexibly mounted to the airframe, and significant coupling may exist between the rotor modes and airframe modes. The rotor control system represents another dynamic system which may couple with either rotor or airframe vibratory modes. Finally, the pilot may interact through the control system to create pilot-induced oscillations. This complicated dynamic system is continuously excited by complicated aerodynamic and inertial forces (represented by the hammer).

Because of the complexity of the aerodynamic and dynamic phenomena encountered by a rotor system it is essential that test conditions accurately represent those to be encountered by the flight vehicle. As explained more completely in reference 13 it is generally not possible to faithfully duplicate on rotor models all of the aerodynamic, dynamic, and mechanical characteristics (i.e., backlash, friction, etc.) of concern. Furthermore, the consequences of an inadequate allowance for any one of these phenomena may result in catastrophic failure of the rotor system. Therefore, full-scale wind tunnel tests of advanced rotor systems prior to flight test at high speed are an essential step in the development of high-performance rotary-wing aircraft. However, the performance levels of some existing and many forecasted advanced rotary-wing aircraft are beyond the capabilities of the 40- by 80-foot wind tunnel, which is the only facility available for this work at present.

High-Disk Loading V/STOL Aircraft

One of the critical problems for fan or jet V/STOL propulsion systems is distorted inlet flow. Effects of distortion are shown schematically in figure 8. Modest amounts of distortion cause modest though important degradations in engine thrust and efficiency. Some critical level of distortion causes engine stall with resulting large losses in thrust, unsteady flows through the engine, blade vibrations with attendant high blade stresses, excessive turbine temperatures, and attendant risk of damage to the engine.

The thrust loss due to engine stall can be catastrophic. For the VTOL airplane the entire airplane weight is supported by the propulsion system at takeoff and landing. The STOL airplane also derives a large measure of its lift from the propulsion system at low speeds. Therefore, it is mandatory to avoid engine stall, and it is desirable to minimize the performance losses associated with lower levels of flow distortion.

The circumstances that lead to flow distortion for lift engines and fans are shown on figure 9, which illustrates a typical lift fan for a VTOL airplane. After the VTOL airplane leaves the ground, the airplane accelerates forward to achieve wing supported flight. During this transition the lift fans must operate in highly distorted flow caused by the air turning approximately ninety degrees to enter the fan. This large turning may induce flow separation at the inlet lip and fan hub which causes further distortions. This highly distorted flow may stall the fan.

Stall in a fan or compressor is associated with the stall of the individual rotor blades and is analogous to the stall of helicopter blades previously discussed. However, the performance of many blades in rows and stages as they occur in a compressor significantly complicates the prediction of compressor stall, and it has been found that each engine design exhibits its own unique characteristics. Thus, the testing of full-scale engines is the only satisfactory way known of determining its stall characteristics.

Another undesirable consequence of engine inlet flow distortion is the generation of noise. While the engine fan and compressor stages generate noise even in a uniform flow, the noise generated by these rotating aerodynamic surfaces is significantly increased in the presence of flow distortion. The noise constraints to be imposed on commercial V/STOL airplanes are very stringent. The precise determination of engine noise and the design of efficient noise suppression systems will depend on tests of full-scale engines in the distorted flow induced by the full-scale airplane.

The economics of full-scale engine testing warrants some comments. It is generally accepted that the building and testing of small-scale, external aerodynamic airplane models is far less expensive than the testing of a full-size model. This however, is not the case with engines. Once a commitment has been made to design and build an engine for an aircraft application, it is usually less expensive to buy demonstrator versions of that engine for research and development purposes than it is to build a half- or quarter-scale model of the engine. This is because changing the scale of the engine by factors of two or four requires an extensive redesign and redevelopment effort to insure satisfactory operation. These factors account for a major portion of an engine model cost and usually exceed the cost of a full scale engine for which the cost of design and development is spread over many engines. Thus, the use of full-scale engine tests in contrast to tests of model engines is the more economical approach, and, in fact, is the only cost-effective way to study problems such as engine stall which were described in the preceding paragraphs.

FULL-SCALE TESTING TO REDUCE PROGRAM RISKS AND COST

The preceding sections of this paper have discussed the potential for application of advanced high-lift and V/STOL aircraft in meeting the transportation needs of the nation, and have reviewed some of the technology problems associated with these aircraft. A related problem is that of convincing the public that the proposed aeronautical systems are, in fact, economically and environmentally viable solutions.

The ability of the aerospace community to present a credible case for advanced aeronautical systems has been seriously eroded by a number of extremely expensive failures of advanced aircraft. These failures have been widely publicized and have prompted considerable criticism. It is clear that this situation must be remedied and public confidence restored in the aerospace community's ability to deliver on its promises.

A number of studies have been conducted to find means of reducing the risk in advanced aircraft programs. One of these (reference 14) examines the role of test facilities in the aircraft development process. According to this study there is a consensus among experienced technical personnel that more use of test facilities would significantly reduce the risk of advanced aircraft programs. This study also concluded that increased use of facilities would improve the performance of the end product. These are the prime justifications for the proposed full-scale subsonic wind tunnel. The use of such a facility to determine the characteristics of critical components of advanced aircraft (e.g., rotors, engines, etc.) before committing large funding to the aircraft program would significantly reduce the program risk. Moreover, this testing could be done prior to selection of the contractor for aircraft fabrication, so that competition could be maintained beyond the paper study phase, and additional data would be available to guide the final selection.

The points made in the preceding paragraph are summarized in figure 10. In brief, it is believed that the full-scale subsonic wind tunnel is required to reduce the risk and cost of advanced aircraft programs. The program risk is reduced by providing tests of critical components early in the program and by maintaining competitive options through this phase. The program cost is reduced by minimizing failures during the subsequent high cost phases of the program, by minimizing expensive flight testing, and by improving the performance of the end product.

An example of how this philosophy is being applied by the NASA and the U.S. Army in the procurement of a tilt-rotor research aircraft is illustrated in figure 11. This figure presents the program cost as a function of time. The cost curve follows the "S" curve typical of most advanced development programs. In the first phase, which involves less than 5 percent of the total cost, full-scale tests of two competitive rotor systems are being conducted to determine their dynamic and performance characteristics. At the conclusion of this phase a single contractor will be selected to build the aircraft. The aircraft itself will be tested in the 40- by 80-foot wind tunnel before the first flight to minimize the possibility of unexpected problems being encountered during flight tests. Figure 12 shows a photograph of one of the rotors for this aircraft installed in the 40- by 80-foot wind tunnel for dynamics testing, and a sketch of the complete aircraft installed in the wind tunnel. As discussed in a later section of this report a similar test program has been followed in the development of a number of experimental aircraft. In many cases the full-scale wind tunnel tests proved to be essential in that deficiencies were found that could have been catastrophic if encountered in flight.

ALTERNATIVES TO A NEW FULL-SCALE WIND TUNNEL

In view of the high cost of a new full-scale wind tunnel a number of alternatives have been considered. A summary of these is provided on figure 13 along with their relative advantages and disadvantages.

The small-scale pressure wind tunnel is a valuable research facility in that it provides the means to independently determine Mach number and Reynolds number effects. However, it is not possible to achieve full-dynamic similarity on models in a pressure wind tunnel, and it can not be used for testing engines. Therefore, it does not meet the testing needs for the full-scale wind tunnel, and was not considered further.

The high-speed track was studied to determine the feasibility of utilizing such a facility to conduct the testing envisioned for the full-scale wind tunnel. However, the high speed track has a number of disadvantages. A prime disadvantage is the high acceleration the test article must be subjected to during starting and stopping. Another disadvantage is the short test time available which is inadequate for careful dynamics testing. Because of these and other deficiencies listed on figure 13 the high speed track was dropped from further consideration.

Another alternative considered was to conduct the proposed full-scale testing in flight, either with prototype aircraft, or with components (e.g., rotors or engines) mounted on existing test aircraft. However, flight testing is expensive in terms of the cost per data point. Further, it is usually not possible to control the test conditions in flight as well as they can be controlled in a wind tunnel. Finally, the consequences of a failure of the test hardware in flight are much more hazardous than the consequences of a failure in the wind tunnel. For these reasons flight testing was not considered to eliminate the need for the full-scale wind tunnel. In fact, a prime objective of the full-scale wind tunnel is to reduce the cost and risk of the flight testing required.

The feasibility of uprating the test capability of the existing 40- by 80-foot wind tunnel has been proposed as an alternative to the proposed new full-scale wind tunnel. However, it does not appear that any feasible modifications to the 40- by 80-foot wind tunnel would provide all of the test capability desired in the new facility. Modifications to the 40- by 80-foot wind tunnel could significantly enhance the full-scale testing capability of this wind tunnel, and may well be justified on their own merit. Therefore, design studies are currently in progress to determine the cost and down-time required to up-grade the test capability of the

40- by 80-foot wind tunnel. The modifications being considered are repowering the wind tunnel to provide a test speed of 300 knots in the existing 40- by 80-foot test section, and the addition of a new 80- by 120-foot low-speed test section.

FULL-SCALE WIND TUNNEL DESIGN STUDIES

Aircraft Size and Speed Trends Relating to Facility Requirements

Conventional aircraft.- Over the years the increasing demands of mission requirements and economics have dictated a long term trend toward larger aircraft. A result of this is that the existing full-scale wind tunnels are no longer capable of testing most operational aircraft. As shown by figure 14, even modern fighter aircraft tax the capability of these facilities. As a result of this, current research and development tests for the F-14 and F-15 fighter aircraft are being performed with 3/4-scale models rather than full-scale test vehicles; and the use of such models will not get at the important interface between structures, propulsion, and aerodynamics.

Rotorcraft.- Figure 15 shows the variation of rotor diameter or aircraft span with gross weight and payload for single rotor compound helicopters and tilt rotor aircraft. These variations result from fairly well-defined limits on rotor disk loading and rotor weight. Therefore, the trends shown on figure 15 can be expected to be valid into the foreseeable future. The largest diameter rotor which can be tested in the 40- by 80-foot wind tunnel is about 60 ft., and, for this size rotor, the tests are limited by wind tunnel wall constraint of the flow to low wake angle conditions (i.e., high speeds and low lift coefficients). Figure 15 shows that, with this limitation on aircraft span, the 40- by 80-foot wind tunnel is far too small to test full-scale transport rotorcraft, and is capable of testing only the smaller utility and tactical aircraft.

Figure 16 shows the increase in the rotorcraft speed records with time, and demonstrates the feasibility of operating advanced rotorcraft up to speeds of the order of 300 knots. However, it should be recognized that the more recent high speed records have been achieved only with small experimental rotorcraft having extremely limited flight envelopes. There is as yet no operational rotary wing aircraft capable of flight speeds over 200 knots. In contrast, the maximum speed of the 40- by 80-foot wind tunnel is only 200 knots. This deficiency in facility speed capability is analogous to that which existed for transonic facilities in the forties which prompted the construction of the X series of high-speed research aircraft.

The economics of transport missions dictates higher flight speeds than are available from current helicopters. Even for relatively modest stage lengths, speeds of 250 to 350 knots are required for economic operation. As discussed previously the most serious technical risks for high-speed rotorcraft are rotor dynamic stability and vibratory loads in high speed flight. The magnitude of these problems can be expected to increase at least with the flight velocity squared. Therefore, the increase in rotorcraft speeds from the current 200-knot level to the 300-knot level can be expected to more than double the rotor dynamic stability and vibration problem.

In summary, the long-term trends in size and speed requirements for advanced rotorcraft indicate a need for vehicles having rotor diameters or spans of up to 100 ft., and capable of flight speeds of 300 to 350 knots. A full-scale wind tunnel capable of testing these rotor systems would require a test section size of at least 60- by 120-feet and a speed of at least 300 knots.

High-disk loading V/STOL aircraft.- Figure 17 (from reference 13) shows the typical variation of aircraft span with gross weight and payload for a variety of high-disk loading V/STOL and STOL transport aircraft concepts. In general, STOL aircraft concepts for which the wing carries a major share of the weight (such as the externally blown flap and the augmentor wing) are near the upper bound of the shaded area on figure 17, while concepts for which the propulsion system carries the major share of the weight (such as lift fan aircraft) are near the lower bound of the shaded area. While the size trends shown on figure 17 for high disk loading V/STOL aircraft are not as well defined as those shown on figure 15 for rotorcraft, they nevertheless indicate that aircraft having wing spans from 60 to 100 ft. will be required to perform the transport missions envisioned for these aircraft.

The primary technical problems for these aircraft are in the low-speed flight range (up to about 150 knots) where there is strong interference between the flow through the propulsion system and that over the airframe. Under these conditions the aircraft wake is deflected through a large angle and the flow constraint effects of the wind tunnel walls become the limiting factor in determining the wind tunnel size requirements. On the other hand, in high speed flight these aircraft are more or less conventional in their operation, and require no special test requirements other than those used for cruise flight of conventional aircraft. Therefore, the test requirements for most high-disk loading V/STOL aircraft can be met in a wind tunnel with a maximum speed capability of 150 knots. However, the effects of the constraint of the flow become increasingly serious as the speed is reduced (and the wake angle is correspondingly increased). Therefore, these aircraft dictate the size requirements of the proposed facility.

Facility Size and Speed Requirements

The aircraft size and speed trends discussed in the preceding paragraphs are summarized on figure 18 along with the approximate test section widths required to accommodate tests of these aircraft. At the lower speeds, corresponding to the transition flight regime of V/STOL aircraft, the size of the test section increases rapidly as the flight speed decreases. This increase in size is required to alleviate the growth of wind-tunnel wall constraint effects with increasing wake angle as the speed is reduced. These test-section width requirements are shown as approximate areas rather than definitive lines since they are dependent on a number of factors. However to conduct tests of large V/STOL aircraft having wing spans of 100 ft. at speeds of 50 knots and less, a test section width of 200 feet is indicated. On the other hand, at the high speeds and low lifts corresponding to the regime of prime interest for advanced rotorcraft, a test-section width of at least 120 ft. would be required.

Wind Tunnel Configuration Studies

A number of wind tunnel configurations have been studied to determine the best compromise between the conflicting speed and size requirements discussed in the preceding section. Some of these designs are shown on figure 19. Broadly speaking, they included a simple closed-return design similar to the 40- by 80-foot wind tunnel but scaled up to a test section size of 75- by 150-foot and a speed of 300 knots, an open-return wind tunnel having the same size and speed characteristics, and a number of two test-section designs. These studies showed that the cost of the structure in a wind tunnel of this size was the most important element of the cost, and this fact focused attention on the open-return wind tunnel designs which minimize the amount of structure.

The main disadvantage of an open-return wind tunnel is that the flow in the test section is not isolated from the effects of external winds. Thus, the flow quality in the test section may vary from day to day unless special attention is paid to the design of the inlet and exhaust sections of the wind tunnel. A number of experimental investigations have been conducted to develop inlet and exhaust sections which will ensure satisfactory flow quality in an open return wind tunnel. The investigations conducted at the Ames Research Center are reported in reference 15, wherein it is concluded that satisfactory flow quality can be achieved in the test section of an open return wind tunnel under nearly all weather conditions prevailing in a moderate environment such as exists at the Ames Research Center.

The main advantages of the open-return wind tunnel are: (1) it provides the minimum structural cost, and (2) it does not require a purging system to eliminate engine exhaust gases from the wind tunnel air flow. This latter point is particularly important for the full-scale wind tunnel since it is intended to operate V/STOL aircraft propulsion systems in it. The power required for an open-return wind tunnel is about the same as that of a closed return wind tunnel, since the kinetic energy lost at the exit of the open-return wind tunnel is about equivalent to the energy lost in the corners of a closed return wind tunnel.

In summary, the cost of an open-return wind tunnel will be less than that of a closed return wind tunnel provided that the cost of the inlet and exit treatment required for satisfactory flow quality in the open-return design is less than the cost of the return circuit, the heat exchanger, and the exhaust gas purging system in the closed-return wind tunnel. The design studies and wind tunnel experiments conducted to date show that satisfactory flow quality can be achieved in an open-return wind tunnel with relatively economical treatment of the inlet and exit sections of the facility.

The concept selected for the proposed full-scale subsonic wind tunnel is shown on figure 20. This is an open-return wind tunnel having two test sections driven by a common power section. The particular combinations of test section size and speed were selected to give the best compromise between the conflicting test requirements for high-disk loading and low-disk loading V/STOL aircraft discussed in the preceding section of this paper. This design provides the maximum test capability for the minimum cost. It also provides for high utilization of the facility since tests can be conducted in one test section while the other test section is being prepared. Finally, it provides an advantage in budgeting for the facility in that the construction can be phased if necessary, with one test section brought into operation initially and the second test section added at some later date.

ECONOMIC CONSIDERATIONS

The overall judgement that must be made in considering the proposed facility is whether the research and development value of the work performed in this facility will justify its cost. Since this facility should have an operational life of at least 25 years, it is obviously impossible to make a detailed and specific cost-benefit analysis. However, it is possible to arrive at a reasonable perspective on the value of the proposed facility by considering two factors: (a) the estimated cost of future aircraft programs and the possible contributions of the full-scale wind tunnel in reducing these costs; and (b) the experience of the existing full-scale wind tunnels.

Costs of Typical Aircraft Programs

The prime justification for the proposed facility is that the cost of the facility is reasonable in terms of the cost of the aircraft programs which it would support, and in terms of the savings that can be realized for these programs over the costs that would be incurred in the absence of the facility. This assessment is difficult to make. However, some perspective on this can be realized by considering the costs of typical aircraft programs such as are described in reference 16.

Figure 21 compares the funding schedule for a typical production aircraft program (from reference 16) with the cost of the proposed facility. Figure 21 shows that the first major input from tests in the facility occurs prior to flight test when both the level of funding and the rate of increase of funding are low. These tests typically would involve full-scale demonstrator hardware of the high-risk items (e.g. rotors, fans, engines) installed in inexpensive "boiler plate" airframe mockups. Data obtained at this early stage of the program has extremely high leverage on program costs, since the funds committed are still low. The second period of major influence of the facility shown on figure 21 corresponds to the early flight test stage.

If unanticipated problems are encountered in flight, the aircraft can be returned to the full-scale wind tunnel for rapid and safe exploration of these problems. The alternative to this is continued flight tests with the accompanying risks to the aircraft and pilot. By the time flight tests can resolve major discrepancies the cost of the program exceeds that of the facility. In addition, by that time commitments have been made such that the cost incurred by changing the design may be as much as the funds expended. Thus, the cost of the proposed facility should be viewed as an insurance premium which reduces the risk of potential losses in advance technology programs to acceptable levels. It is quite likely that, without the assurance provided by early tests of critical components in the proposed facility, many advanced aircraft programs (e.g., high-speed rotorcraft and V/STOL aircraft) will not be initiated due to excessive technical and financial risk.

Experience with Existing Full-Scale Wind Tunnels

NASA has operated full-scale wind tunnels since the late 1920's, and there is considerable historical evidence of the value of this type of facility. The first NASA full-scale wind tunnel (the 20-foot Propeller Research Wind Tunnel) showed the absolute necessity of using cowls for radial engines and variable pitch propellers for high performance aircraft. The incorporation of these features provided the first high performance transports which launched the era of practical commercial air transportation. Similarly, the application of this research to fighter aircraft culminated in the high-performance radial engine fighters of World War II fame.

While the prime justification for both the 30- by 60- and the 40- by 80-foot wind tunnels was for drag reduction studies of military aircraft, the major contributions of these facilities have been in technological areas which were not anticipated at the time the facilities were planned. The contributions of these facilities to the research and development of V/STOL aircraft is an example of this. The

40- by 80-foot wind tunnel has more than paid for itself by preventing failures of experimental V/STOL aircraft in flight. These aircraft encountered failures during tests in the 40- by 80-foot wind tunnel which could have been catastrophic in flight. All of these failures involved the complicated interface between aerodynamics, dynamics, and structures. Therefore, tests of the full-scale hardware were the only way that these problems could have been discovered. For example, the XV-1 compound helicopter encountered a rotor speed instability during the wind tunnel tests which required changes to the rotor control system. Tests of the XV-3 in the 40- by 80-foot wind tunnel were requested after a catastrophic rotor-pylon whirl instability was encountered in flight, resulting in loss of the aircraft and serious injury to the pilot. After two tests in the 40- by 80-foot wind tunnel, separated by a one-year analysis effort, this stability problem was alleviated so that a highly successful flight research program could be completed. As a result, the tilt rotor aircraft is considered today to be one of the more promising high performance rotary wing aircraft concepts. The first wind tunnel test of the XH-51 rigid-rotor helicopter ended in a break-up of the rotor due to a bonding failure. The rotor blade was redesigned, a successful wind tunnel test was completed, and the XH-51 went on to a highly successful flight research program which culminated in a rotorcraft speed record. During wind tunnel tests of the XV-5A lift-fan airplane, structural failure of the fan inlet guide vanes was encountered. If these had failed in flight and entered the fan rotor the aircraft would have been lost. Also, excessive deflection of the fan exit louver control mechanism was encountered during these wind tunnel tests. This would have severely limited the fan-supported flight envelope of the XV-5A. Both of these problems were remedied following the wind tunnel tests, and the XV-5A airplane has completed a series of successful flight research programs. The lift-fan propulsion system is currently considered to be one of the most promising concepts for a high performance V/STOL airplane.

The total cost of the aircraft programs which have been saved by tests of the full-scale aircraft in the 40- by 80-foot wind tunnel has more than offset the total cost of construction and operation of this facility for 25 years. To these savings could be added the savings due to the cancellation of flight test programs of aircraft which had been shown by full-scale wind tunnel tests to have fundamental deficiencies. A partial list of such aircraft is the Kaman K-16 tilt wing, the Avrocar, and the Vanguard low-disk loading fan-in-wing airplane.

Actually, the most important contributions of the full-scale wind tunnels have been in research areas where it is nearly impossible to put a firm dollar magnitude on the value of the contribution. The contributions of the full-scale wind tunnels to the development of the externally-blown flap and the augmentor wing turbofan STOL aircraft are almost solely responsible for the fact that these concepts are today considered to be the most promising types for application to large commercial and military STOL transport aircraft. The use of the full-scale wind tunnels was also instrumental in establishing the feasibility of conventional landings of lifting body spacecraft. This included tests of all of the full-scale flight vehicles in the 40- by 80-foot wind tunnel plus studies of free-flight models in the 30- by 60-foot wind tunnel. These studies added immeasurably to the confidence level required before flight tests could be initiated with these radically new and different aircraft. This is perhaps the best example of an application of the full-scale wind tunnels to fill a need which could not have been anticipated when the facilities were justified.

Since the cost of the proposed full-scale wind tunnel has already been compared with the typical cost of current aircraft programs, it is of interest to compare the cost of the existing full-scale wind tunnels with representative aircraft current at the time these facilities were justified. This comparison is presented on figure 22 which shows the variation in airplane cost and wind tunnel cost with time. This figure shows that the cost of the proposed full-scale wind tunnel relative to the cost of current aircraft is, if anything, less than the cost of the 30- by 60- and 40- by 80-foot wind tunnels relative to aircraft costs at the time these facilities were built. In addition, the need and the potential for both military and civil air transportation is much more apparent now than it was at the time the existing full-scale facilities were justified. In retrospect our predecessors showed a high degree of foresight and courage in building these facilities during the great depression

D

(the 30- by 60-foot wind tunnel) and at the outset of World War II (the 40- by 80-foot wind tunnel).

CONCLUSIONS

The following conclusions were drawn from the studies discussed in this paper:

1. Basic factors such as growth of the population and economy will create a growing demand for transportation in the United States, and the major portion of this transportation demand will be for trips between 50 and 500 miles.

2. The problems of aircraft noise and air traffic congestion must be alleviated if this demand for air transportation is to be met. The use of V/STOL aircraft will provide significant reductions in air traffic congestion by shifting most of the short-haul traffic away from the major airports to small V/STOL ports. In addition, the use of V/STOL aircraft will subject less land area to high noise levels than will surface transportation systems.

3. There are a number of military missions which require the development of high-performance V/STOL aircraft.

4. The major problem associated with the development of advanced V/STOL aircraft is the technical and financial risk of the aircraft development program. This risk can be significantly reduced by conducting full-scale tests of the critical components of the aircraft (e.g., V/STOL propulsion systems and rotors) prior to the go-ahead for the complete aircraft system. To conduct these tests, a subsonic wind tunnel capable of

testing vehicles with spans up to 100 feet and at speeds of about 300 knots is required.

5. While the primary justification for the new full-scale wind tunnel is for the development of V/STOL aircraft, experience with the existing full-scale wind tunnels shows that this facility will be very useful in the development of conventional aircraft as well.

6. A two-test section, open-return wind tunnel provides the maximum test capability for the minimum cost.

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MAJOR PROBLEM AREAS AND ASSOCIATED TECHNOLOGY FOR CIVIL AIR TRANSPORTATION*

PROBLEM AREAS

- NOISE
- CONGESTION
- SHORT HAUL SYSTEMS

ASSOCIATED TECHNOLOGY

- HIGH-LIFT AND V/STOL AERODYNAMICS
- PROPULSION
- ACOUSTICS
- AVIONICS

*CIVIL AVIATION R AND D POLICY STUDY, NASA SP-266

Figure 1

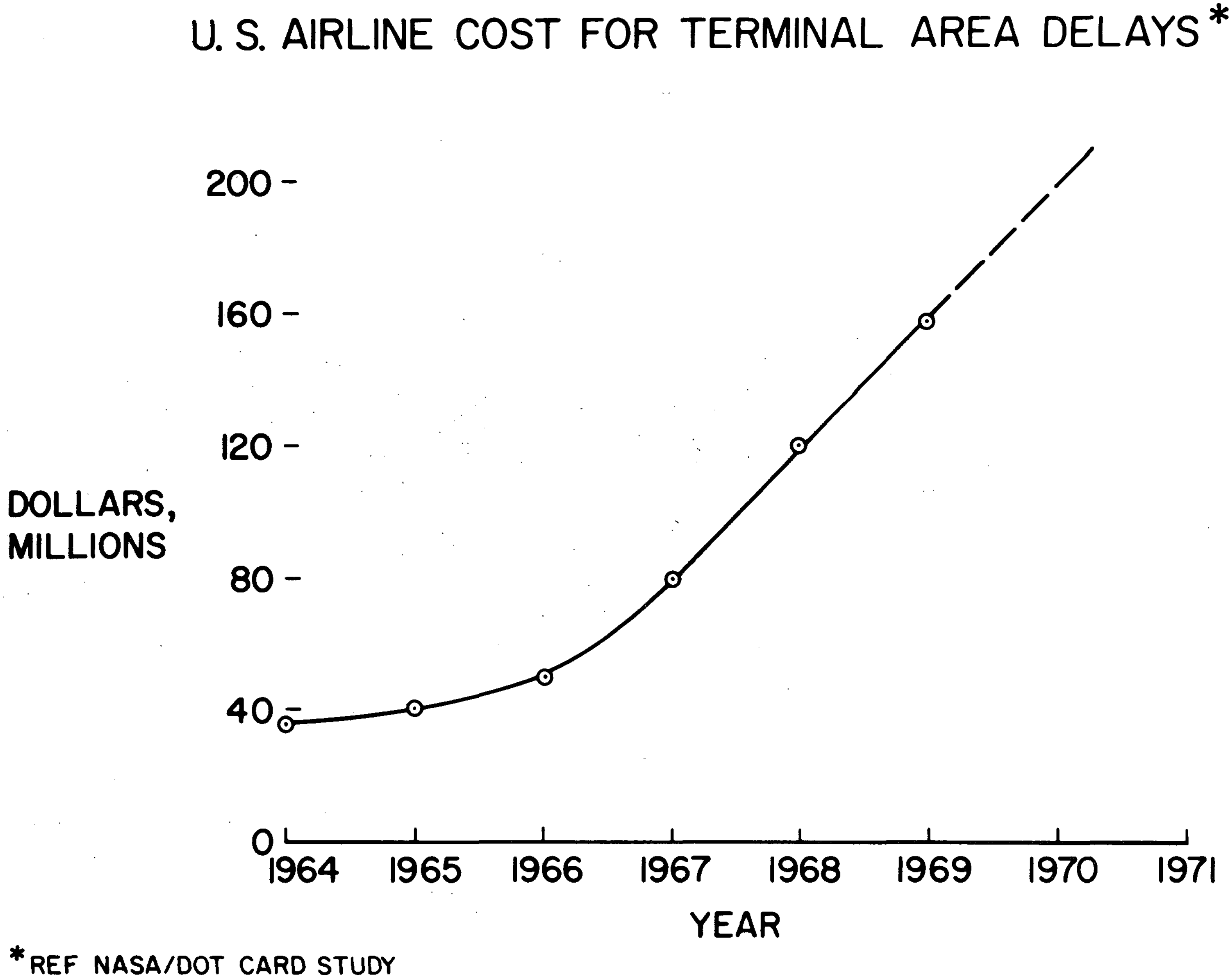

U. S. AIRLINE COST FOR TERMINAL AREA DELAYS*
200
160
120
80
40
0
DOLLARS, MILLIONS
1964
1965
1966
1967
1968
1969
1970
1971
YEAR
*REF NASA/DOT CARD STUDY

Figure 2

COMMERCIAL V/STOL AIRCRAFT

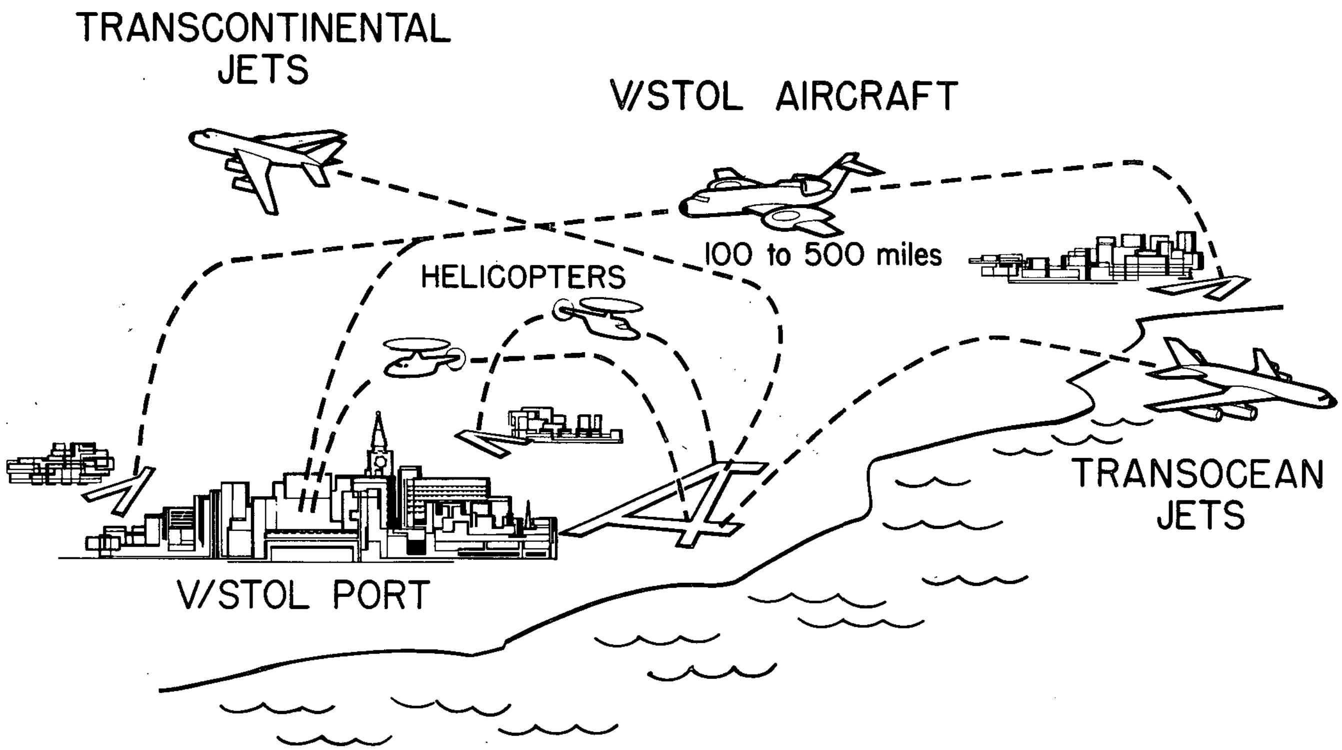


Figure 3

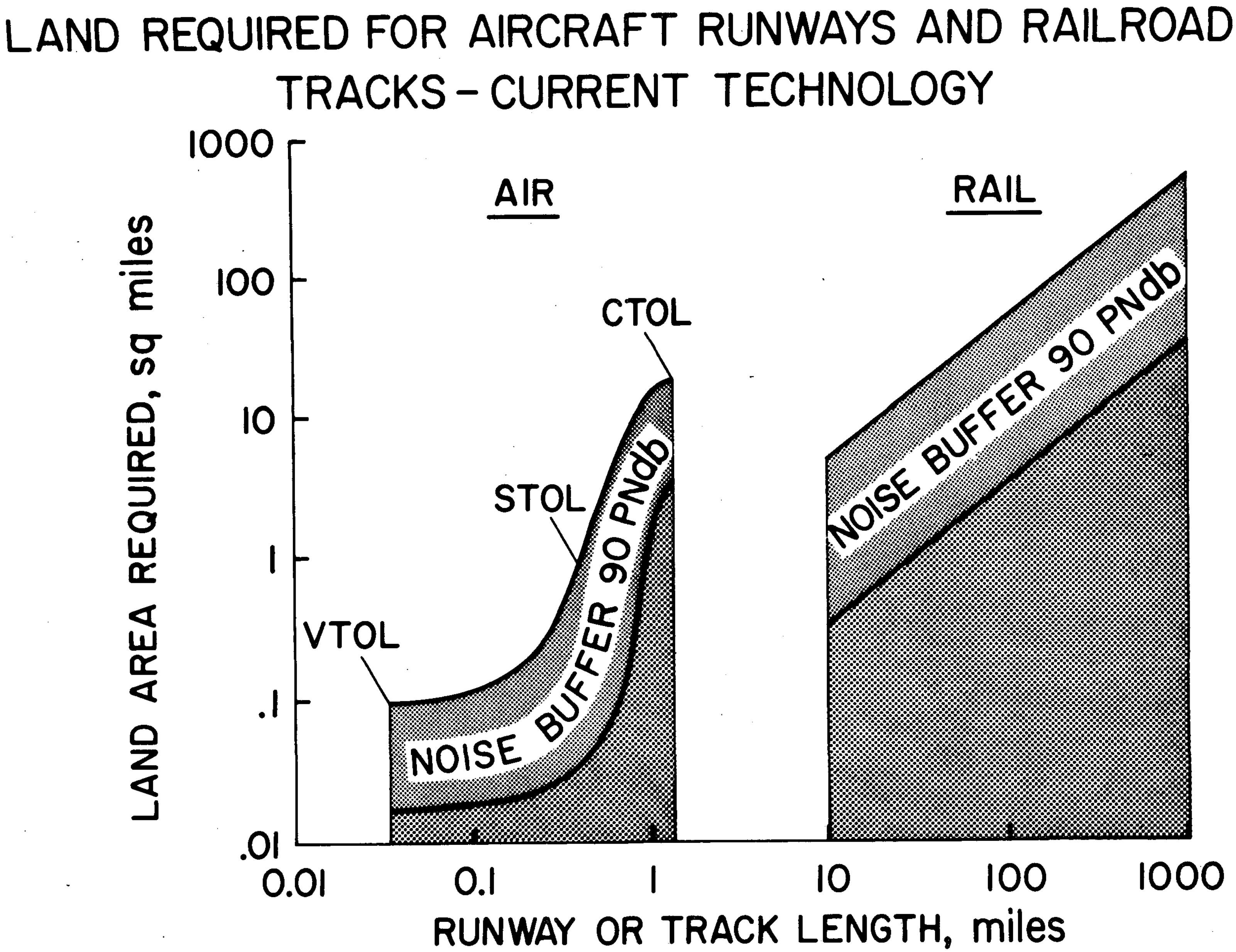

LAND REQUIRED FOR AIRCRAFT RUNWAYS AND RAILROAD TRACKS - CURRENT TECHNOLOGY
AIR
RAIL
CTOL
STOL
VTOL
NOISE BUFFER 90 PNdb
NOISE BUFFER 90 PNdb
LAND AREA REQUIRED, sq miles
1000
100
10
1
.1
.01
0.01
0.1
1
10
100
1000
RUNWAY OR TRACK LENGTH, miles

Figure 4

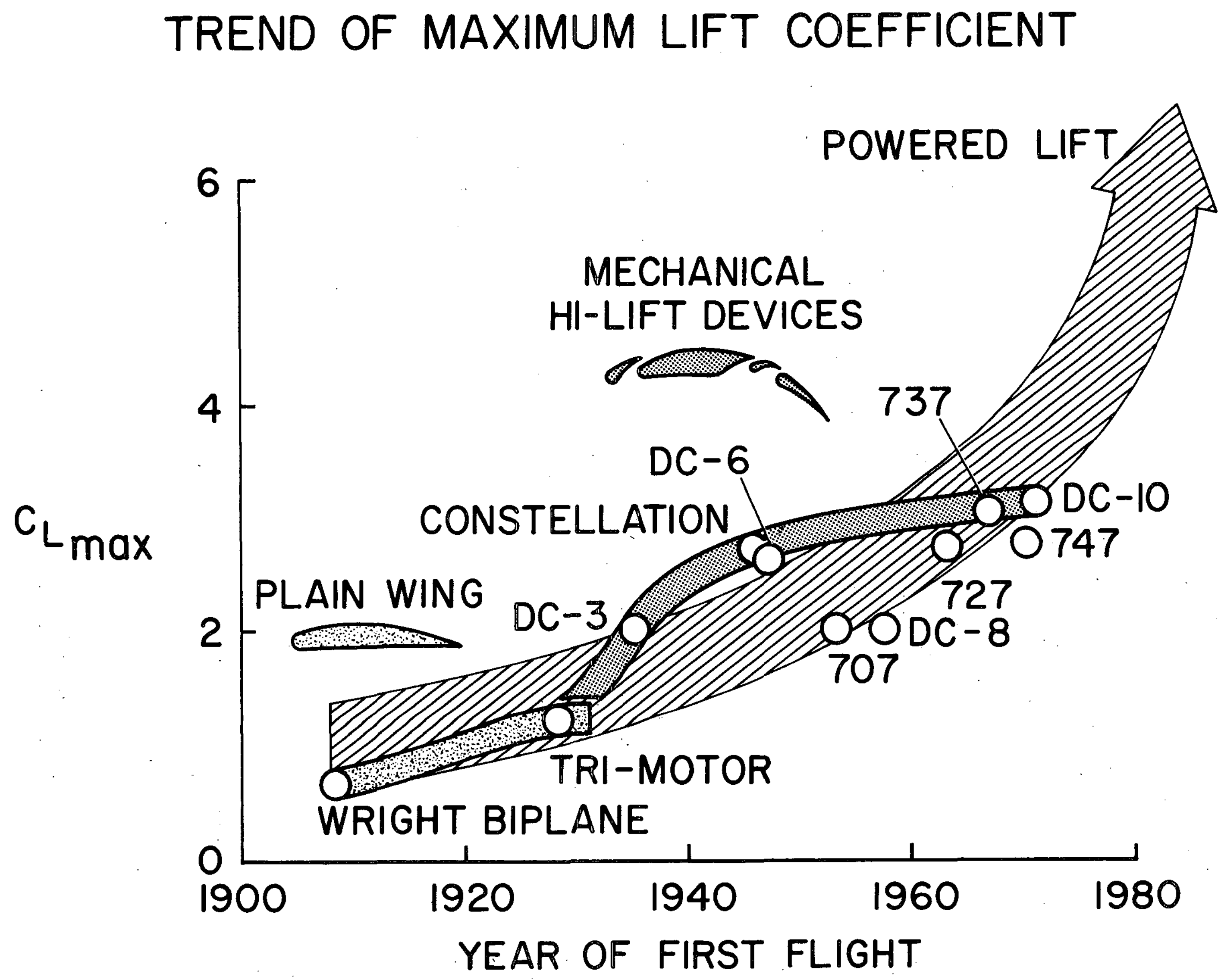

TREND OF MAXIMUM LIFT COEFFICIENT
POWERED LIFT
MECHANICAL
HI-LIFT DEVICES
737
DC-6
DC-10
CONSTELLATION
747
$C_{L_{max}}$
727
PLAIN WING
DC-3
DC-8
707
TRI-MOTOR
WRIGHT BIPLANE
0
2
4
6
1900
1920
1940
1960
1980
YEAR OF FIRST FLIGHT

Figure 5.

ROTOR TRANSIENT AERODYNAMICS
FULL CYCLE IN 1/5 second

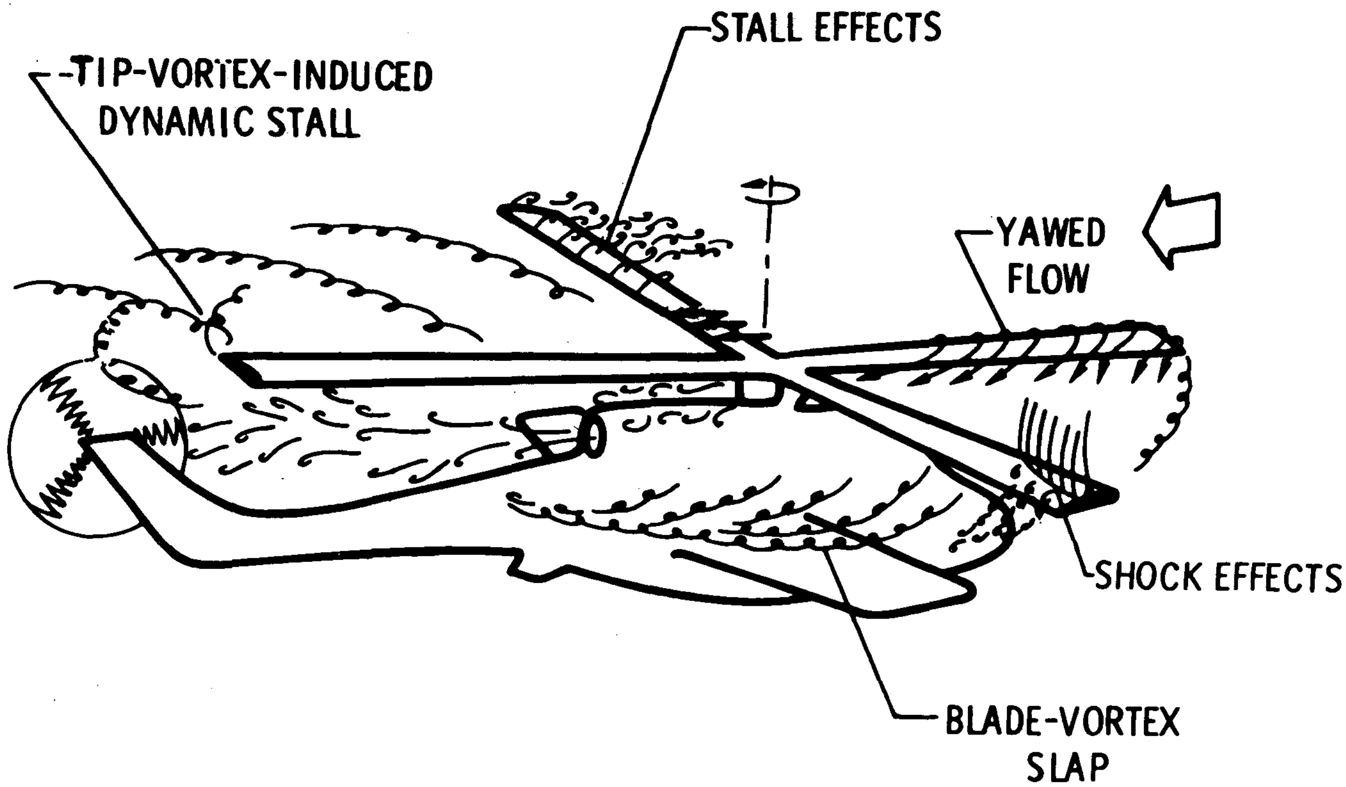


Figure 6

DYNAMICS COMPLEXITY

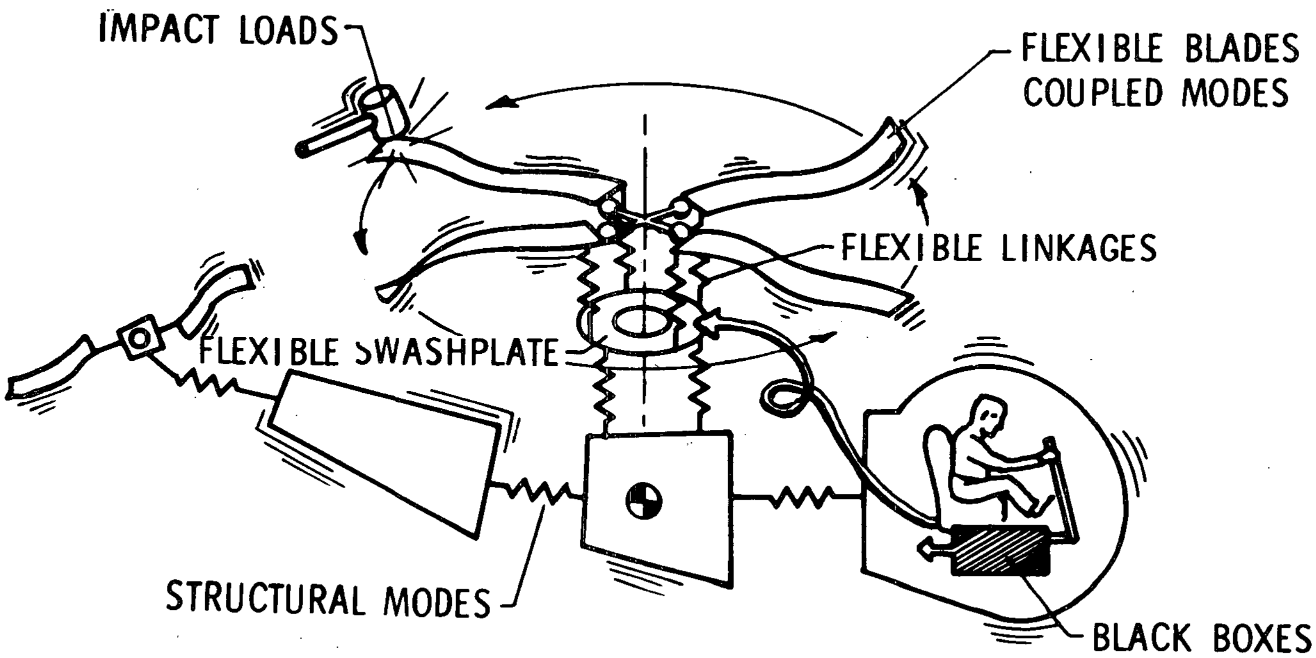
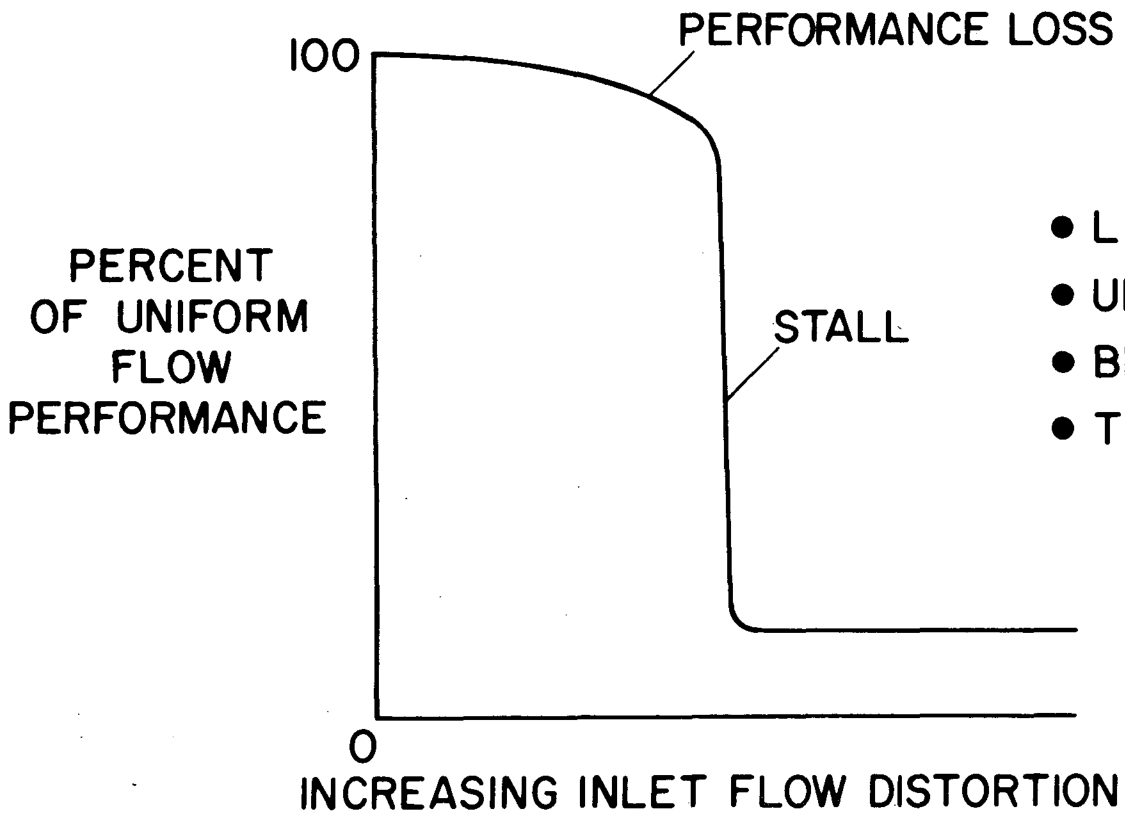


Figure 7

EFFECT OF FLOW DISTORTION ON ENGINE PERFORMANCE



- LARGE THRUST LOSS
- UNSTEADY FLOW
- BLADE VIBRATION
- TURBINE OVER TEMPERATURE

Figure 8

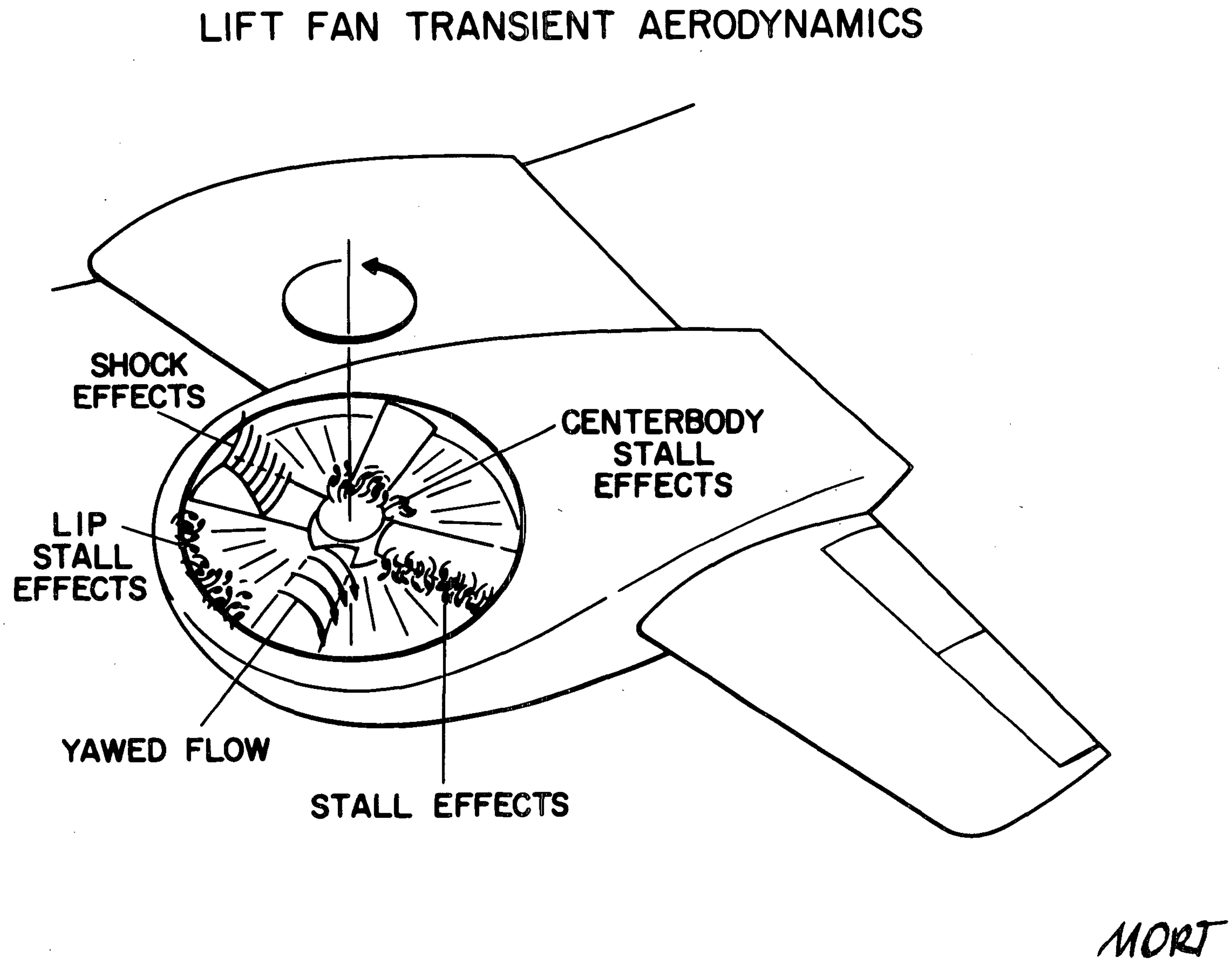

LIFT FAN TRANSIENT AERODYNAMICS
SHOCK EFFECTS
CENTERBODY STALL EFFECTS
LIP STALL EFFECTS
YAWED FLOW
STALL EFFECTS
MORT

Figure 9

THE NEED FOR FULL-SCALE TESTING

- REDUCE PROGRAM RISK
  - TEST CRITICAL COMPONENTS EARLY IN PROGRAM
  - MAINTAIN COMPETITIVE OPTIONS THRU CRITICAL COMPONENT EVALUATION
  - MILESTONE CHECKS OF HARDWARE PERFORMANCE
- REDUCE PROGRAM COST
  - AVOID CRITICAL FAILURES DURING HIGH COST PORTIONS OF PROGRAM
  - MINIMIZE EXPENSIVE FLIGHT TESTING
  - IMPROVE PERFORMANCE AND ECONOMICS OF END PRODUCT

Figure 10

USE OF FULL SCALE WIND TUNNEL FOR TILT ROTOR RESEARCH AIRCRAFT

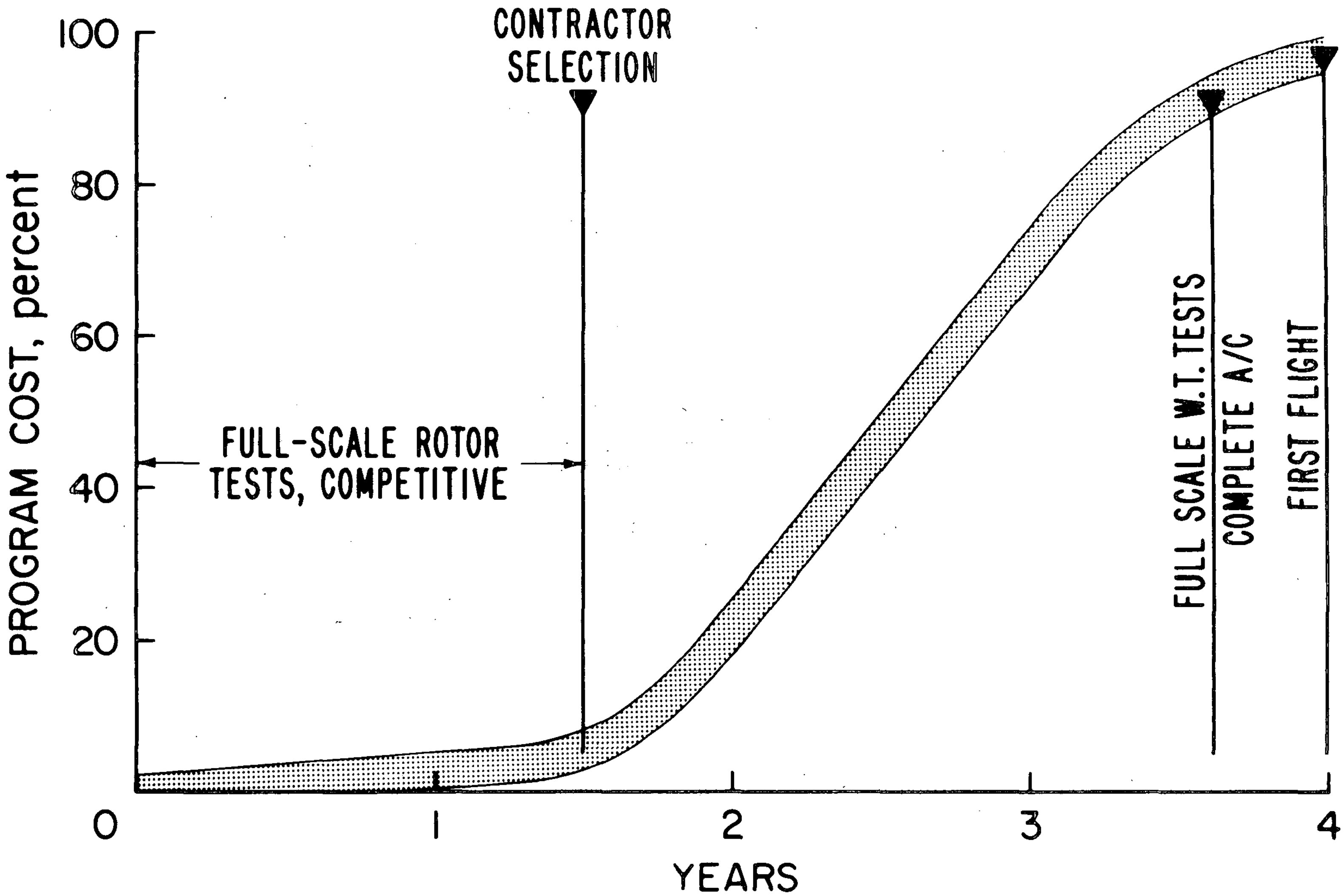
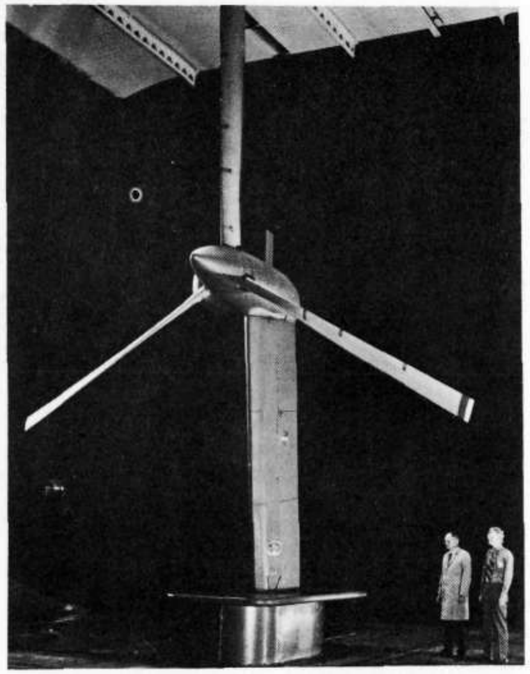
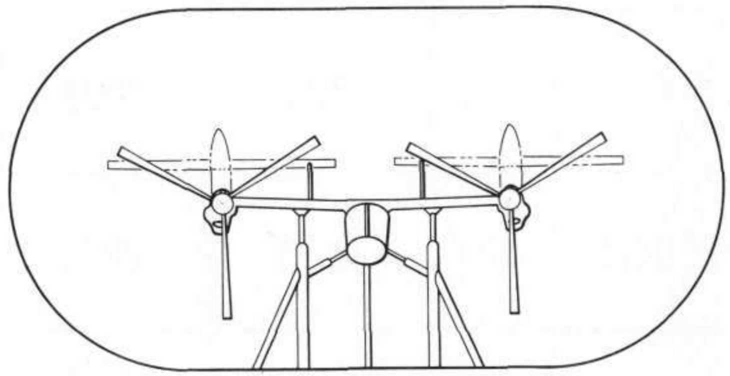


Figure 11

ROLE OF 40×80 ft WIND TUNNEL IN TILT ROTOR AIRCRAFT DEVELOPMENT



SINGLE ROTOR



COMPLETE RESEARCH AIRCRAFT

Figure 12

ALTERNATIVES TO FULL-SCALE WIND TUNNEL

	ENGINE TEST	STRUCTURAL TEST	DYNAMICS TEST	ACCURACY	RISK	COST/DATA PT.
PRESSURE WIND TUNNEL	NO	NO	POOR	HIGH	LOW	MODERATE
HIGH SPEED TRACK	POOR	YES	POOR	LOW	HIGH	HIGH
FLIGHT TEST	YES	YES	YES	MODERATE	HIGH	HIGH
MODIFY 40×80 ft WIND TUNNEL	YES	YES	YES	HIGH	LOW	MODERATE
FULL-SCALE WIND TUNNEL	YES	YES	YES	HIGH	LOW	MODERATE

Figure 13

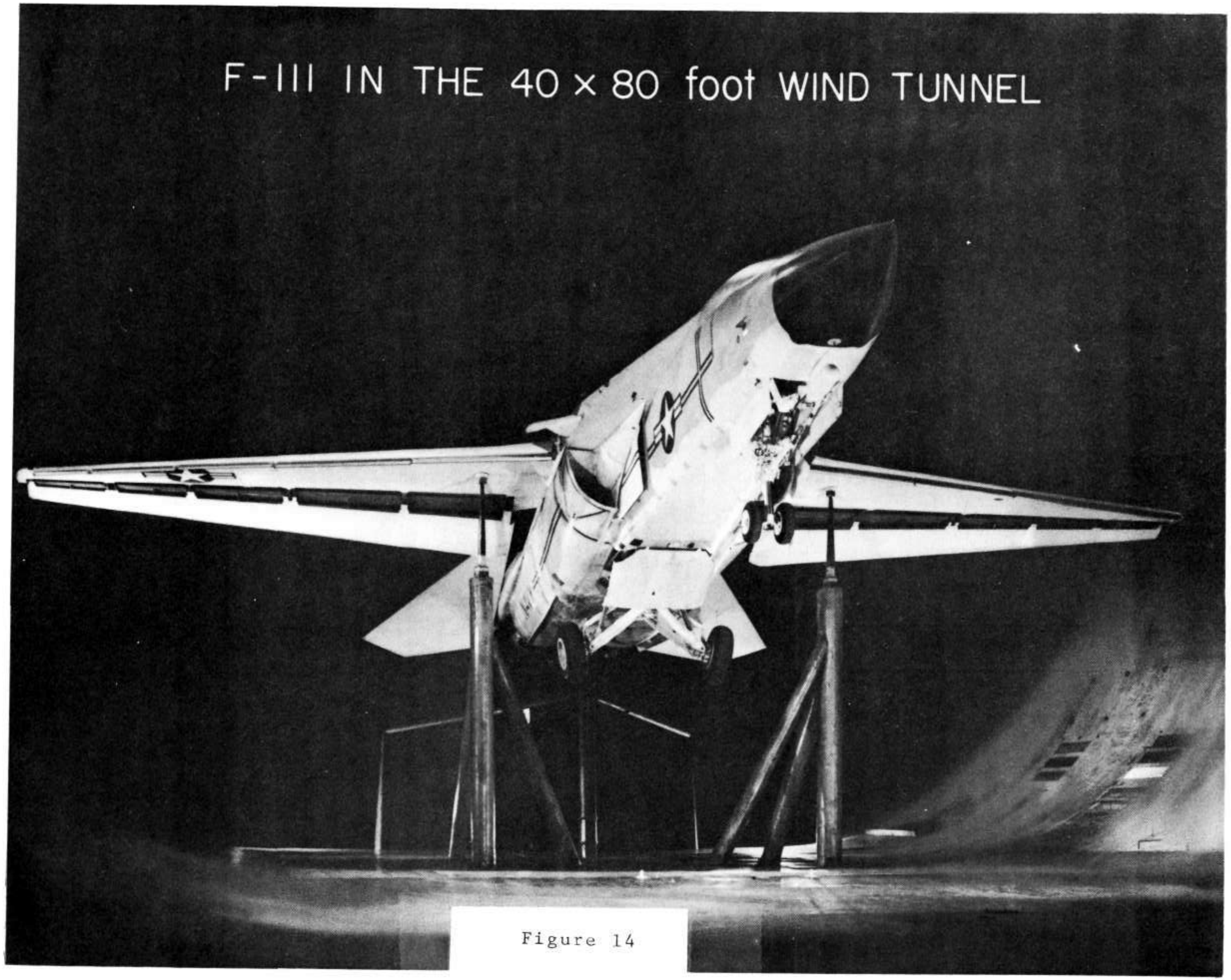


Figure 14

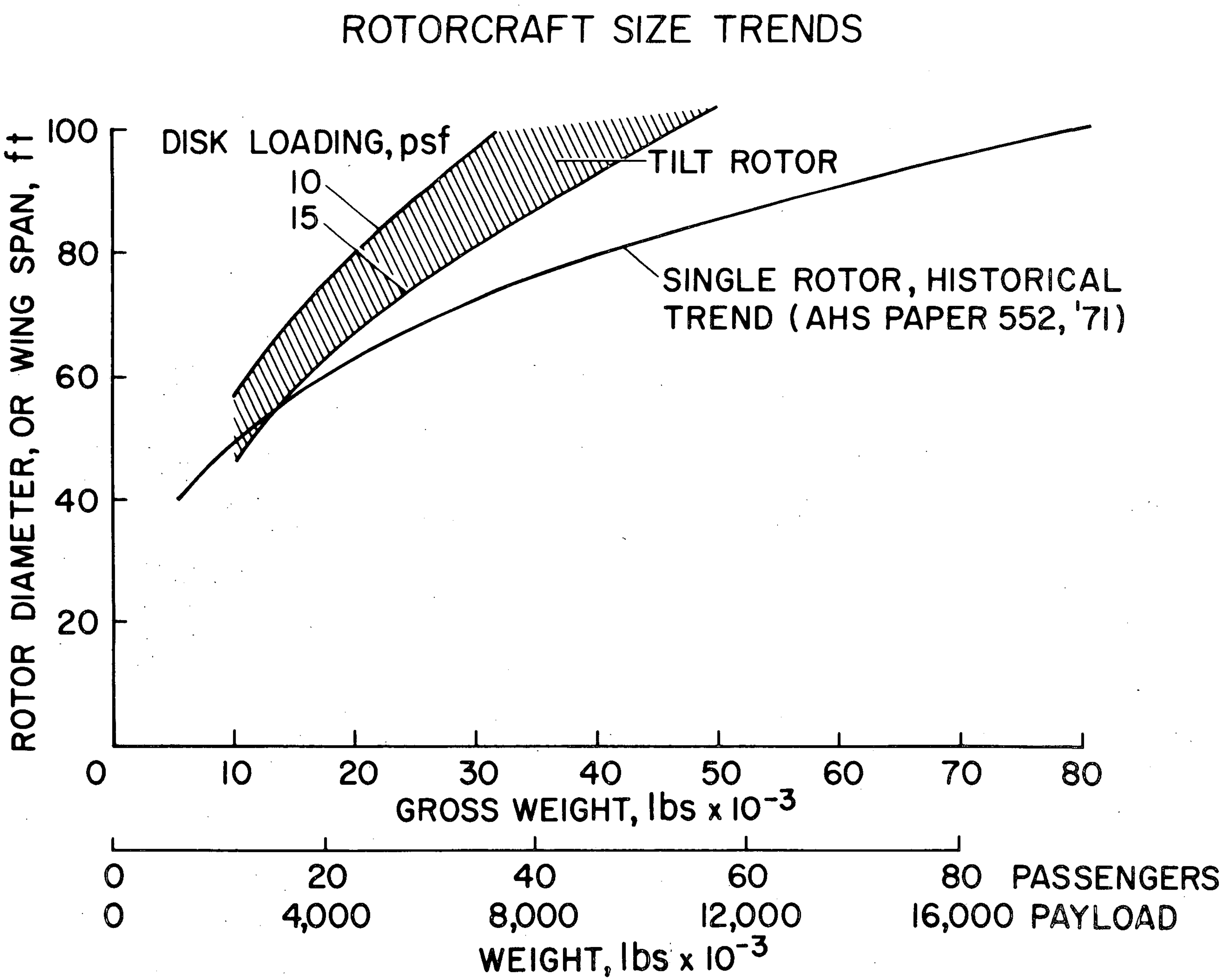

ROTORCRAFT SIZE TRENDS
DISK LOADING, psf
10
15
TILT ROTOR
SINGLE ROTOR, HISTORICAL TREND (AHS PAPER 552, '71)
ROTOR DIAMETER, OR WING SPAN, ft
100
80
60
40
20
0
10
20
30
40
50
60
70
80
GROSS WEIGHT, lbs x 10^-3
0
20
40
60
80 PASSENGERS
0
4,000
8,000
12,000
16,000 PAYLOAD
WEIGHT, lbs x 10^-3

Figure 15

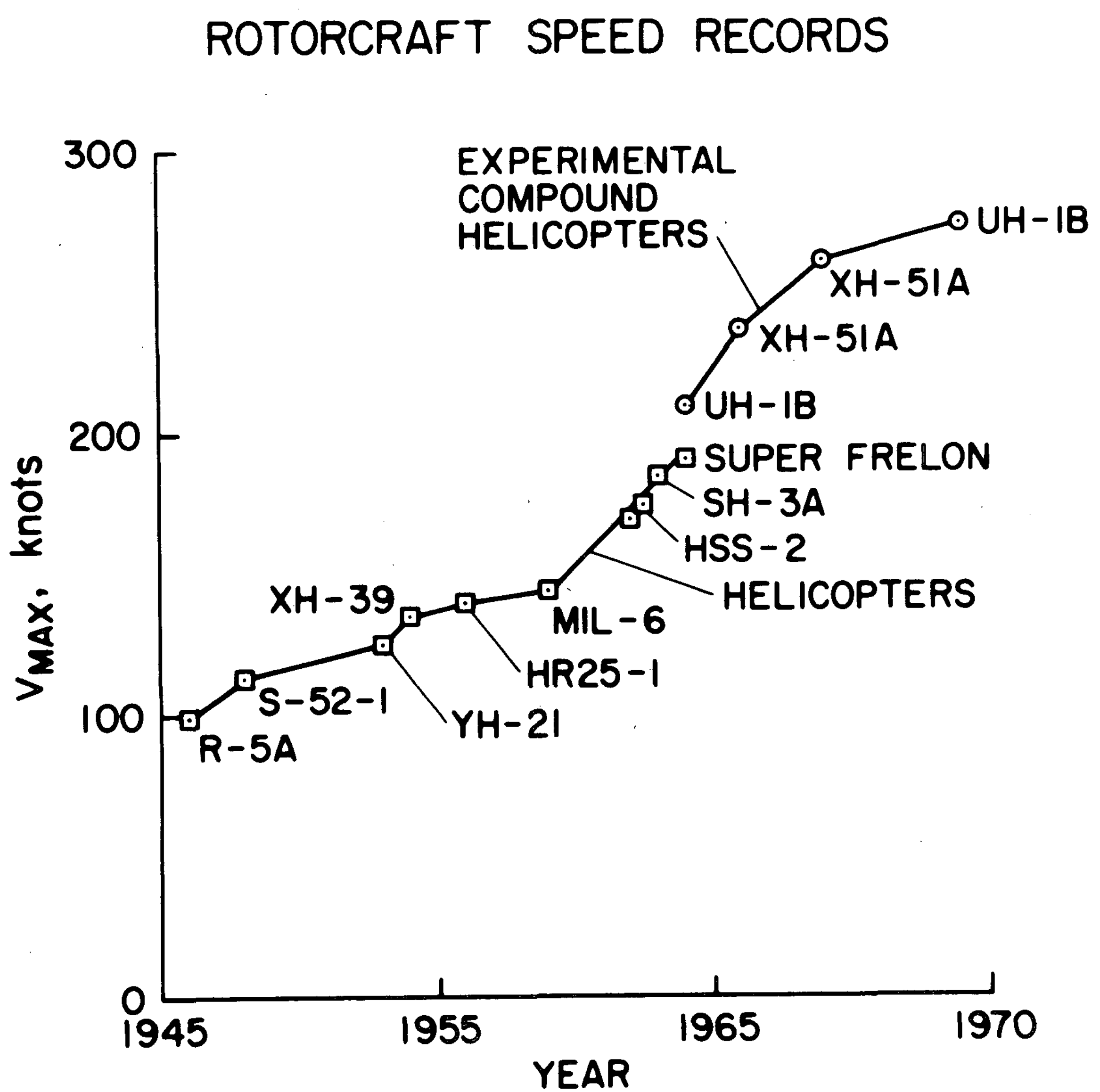

ROTORCRAFT SPEED RECORDS
300
200
100
0
V_{MAX}, knots
EXPERIMENTAL
COMPOUND
HELICOPTERS
UH-1B
XH-51A
XH-51A
UH-1B
SUPER FRELON
SH-3A
HSS-2
HELICOPTERS
XH-39
MIL-6
HR25-1
S-52-1
YH-21
R-5A
1945
1955
1965
1970
YEAR

Figure 16

HIGH DISK LOADING V/STOL AIRCRAFT SIZE TRENDS

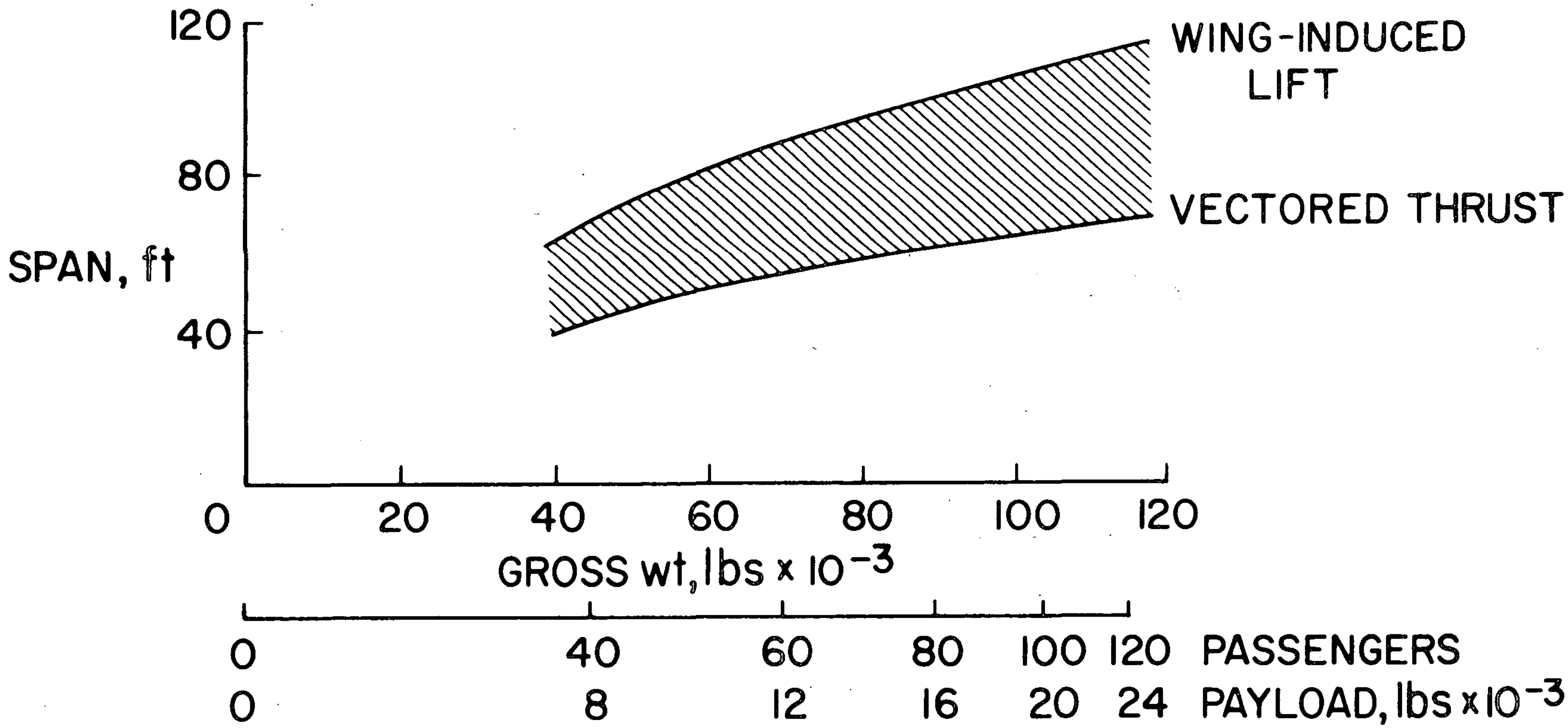


Figure 17

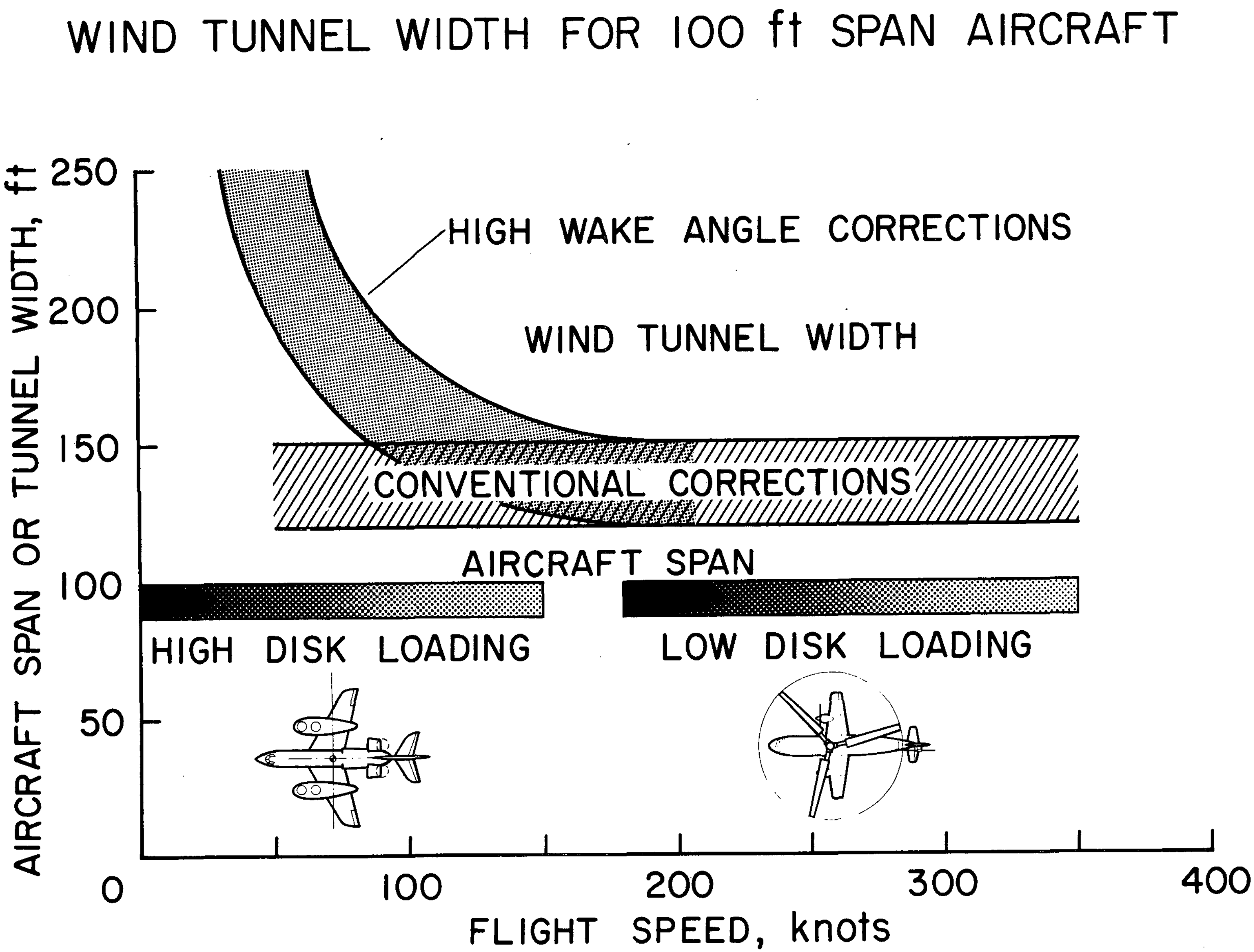
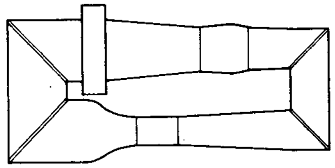
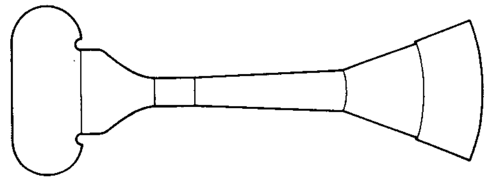

WIND TUNNEL WIDTH FOR 100 ft SPAN AIRCRAFT
HIGH WAKE ANGLE CORRECTIONS
WIND TUNNEL WIDTH
CONVENTIONAL CORRECTIONS
AIRCRAFT SPAN
HIGH DISK LOADING
LOW DISK LOADING
AIRCRAFT SPAN OR TUNNEL WIDTH, ft
250
200
150
100
50
0
100
200
300
400
FLIGHT SPEED, knots

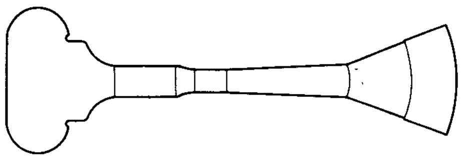
Figure 18

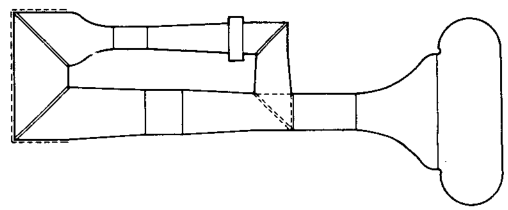
REPRESENTATIVE CANDIDATE CONFIGURATIONS

TEST SECTION SIZE, ft × ft	SPEED, kts
75 × 150	300
75 × 150	300
110 × 165 60 × 120	124 350
130 × 200 60 × 120	150 350
130 × 200 75 × 150	150 300









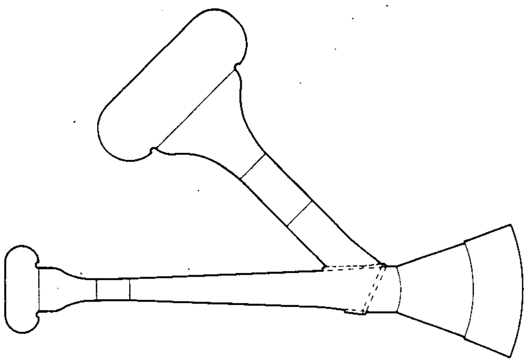


Figure 19

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

WIND TUNNEL CONFIGURATION

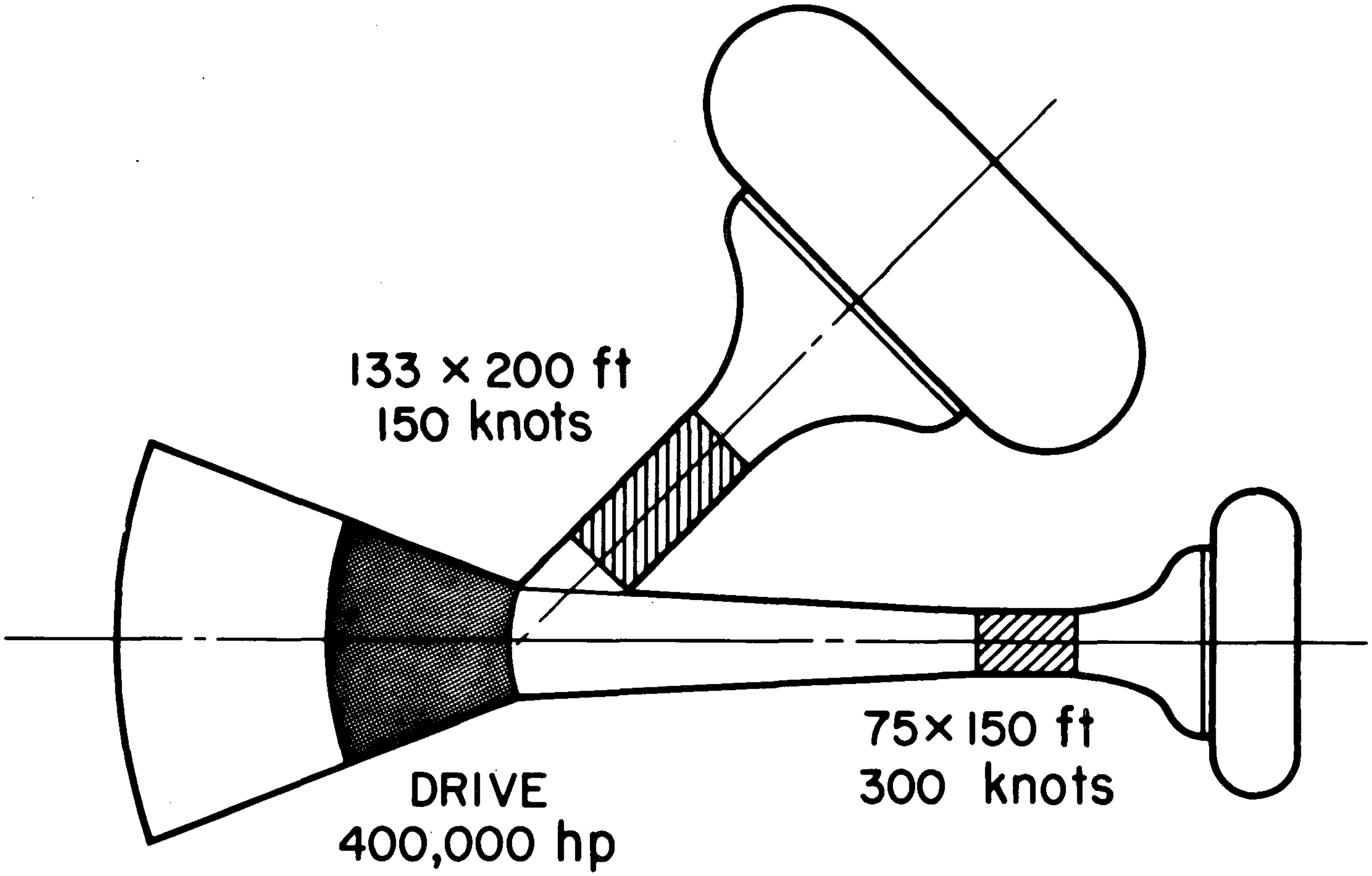


Figure 20

TYPICAL AIRCRAFT FUNDING SCHEDULE AND DECISION POINTS SHOWING TEST LEVERAGE
(CUMULATIVE)

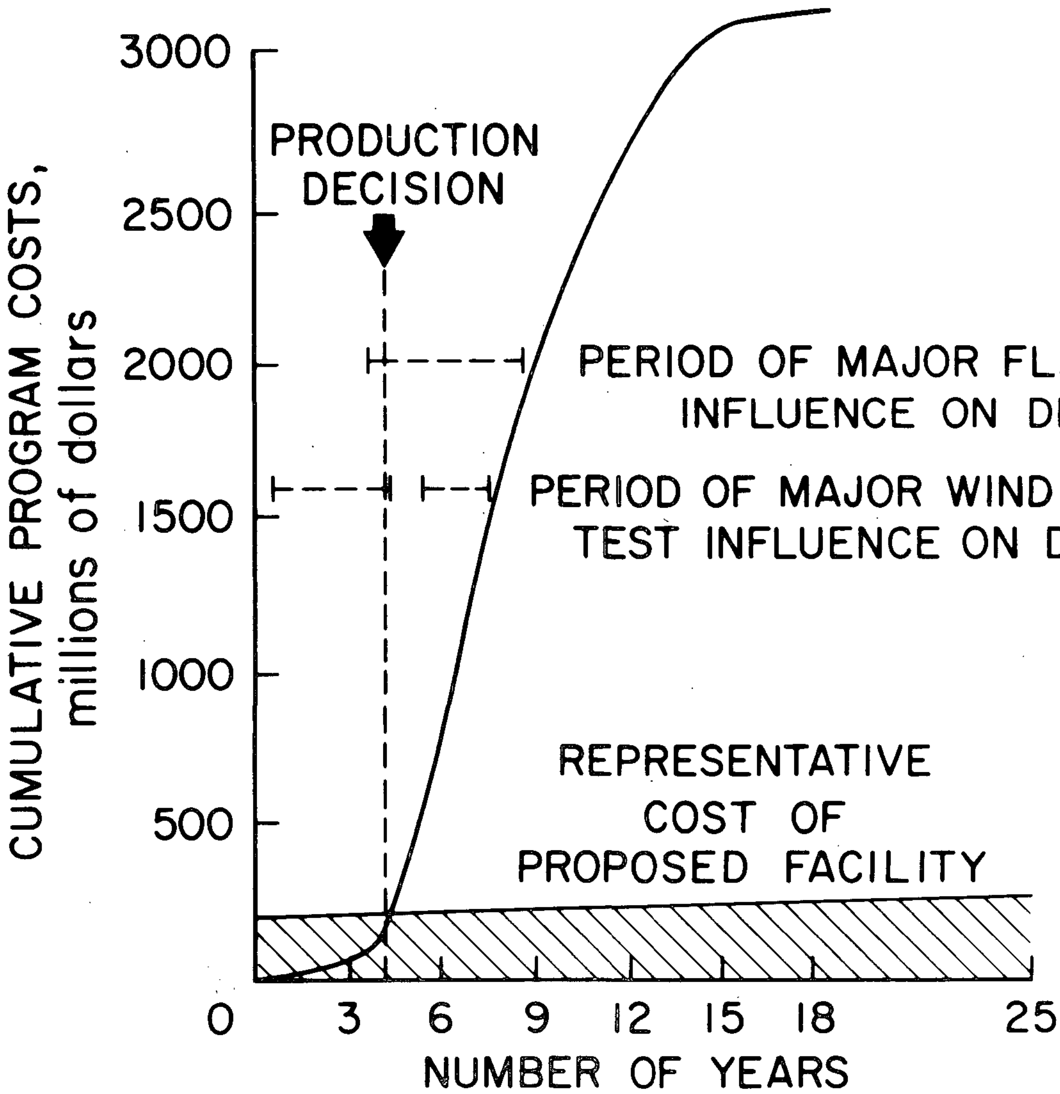


Figure 21

COST OF FULL SCALE WIND TUNNELS RELATIVE TO AIRCRAFT COST

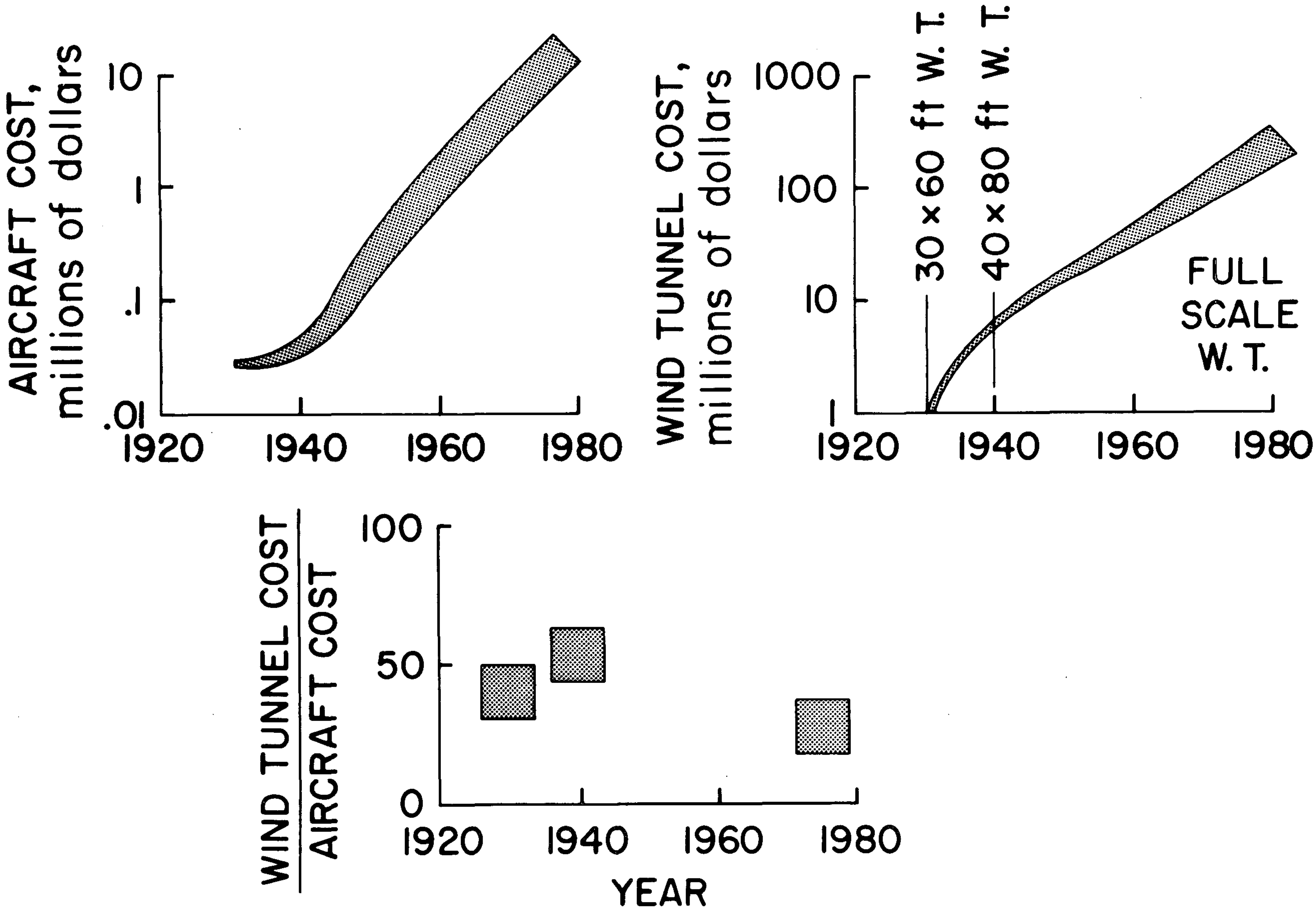


Figure 22